University of Alberta

INTRINSIC BIOREMEDIATION OF CHLORINATED HYDROCARBONS AT COLD TEMPERATURES

by

Anjum Mullick

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science

in

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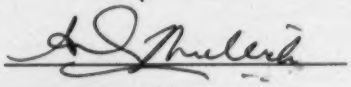

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DEDICATION

This work is dedicated with all my love to my parents, Prakash and Asha Mullick for their encouragement and support, and especially to Fernando Sacluti for all of his time, patience and tolerance during the course of this thesis.

ABSTRACT

Several contaminated sites in the United States have been evaluated for intrinsic bioremediation, but its application in colder temperatures has not been well addressed. The feasibility of intrinsic bioremediation of chlorinated aromatic hydrocarbons at the former landfill site at the Canadian Forces Base (CFB) Cold Lake was studied. The site was previously used for disposing of various hydrocarbon-based products such as oils, solvents and degreasers. The compounds of environmental concern that have been detected include benzene, toluene, ethylbenzene, xylenes (BTEX), 1,1,1-trichloroethane, 1,1-dichloroethane, 1,2-dichloroethane and dichlorobenzenes. The research undertaken involved four separate phases: 1) site investigation; 2) analysis of contaminant concentrations and terminal electron accepting processes across the site; 3) laboratory microbial study; and 4) computer fate and transport modeling.

Results from the geochemical and contaminant investigation, Most Probable Number (MPN) studies and screening level computer modeling suggest that reductive dechlorination and BTEX mineralisation can and is proceeding at the site, despite the colder in-situ temperatures (8°C). Although there is considerable evidence in favour of intrinsic bioremediation as a remedial option, it is believed that continued long-term monitoring should be implemented to better understand the contaminant behaviour. This has been suggested due to the anomalous findings and uncertainty concerning the possible additional source(s) of 1,1,1-trichloroethane at the site.

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ABBREVIATIONS

°C	degree Celsius
°K	degree Kelvin
1 CEU	1 Construction Engineering Unit
1-D	One dimensional
3-D	three-dimensional
AFCEE	Air Force Centre for Environmental Excellence
An-Geo	An-Geo Environmental Consultants Ltd.
BC	biodegradation curve
BTEX	benzene, toluene, ethylbenzene and xylenes
CA	chloroethane
Ca^{+}	calcium
CAH	chlorinated aliphatic hydrocarbon
CCMA	Council of Ministers of the Environment
CH_4	methane gas
cm	centimetre
CO_2	carbon dioxide
CO_3^{2-}	carbonate
C_u	coefficient of uniformity
1,1-DCA	1,1-dichloroethane
DCC	Defence Construction Canada
DNAPL	dense non-aqueous phase liquid
DND	Department of National Defence
DO	dissolved oxygen
EM	Electromagnetic Induction Survey
ETL	Enviro-Test Laboratories
Fe^{2+}	ferrous iron
Fe^{3+}	ferric iron or iron (III)
FeRB	iron-reducing bacteria
ft/yr	feet per year
g	gram
g/L	grams per litre
g/mol	grams per mole
GC	gas chromatograph
HCO_3^{-}	bicarbonate
IB	intrinsic bioremediation
IWR	IWR Technologies Ltd.
K	hydraulic conductivity
K^{+}	potassium
kg/L	kilogram per litre
K_z/K_R	anisotropy ratio
L	litre
L/kg	litres per kilogram
LEL	lower explosive limit
LNAPL	light non-aqueous phase liquid
m	metre

ABBREVIATIONS (continued)

m/s	metres per second
m/yr	metres per year
mg/kg	milligram per kilogram
mg/L	milligram per litre
Mg^{+}	magnesium
mL	millilitre
mm	millimetre
mmol	millimole
Mn^{4+}	Manganese ion
MNA	monitored natural attenuation
mol/L	mol per litre
MPN	Most Probable Number
mV	millivolts
N_2	Nitrogen gas
Na^{+}	sodium ion
NAPL	non-aqueous phase liquid
NBC	no-biodegradation curve
ND	non-detectable
NO_2^{2-}	nitrite ion
NO_3^{-}	nitrate ion
NRB	nitrate reducing bacteria
O_2	oxygen gas
OH^{-}	hydroxide
ORP	oxidation-reduction potential
OSWER	Office of Solid Waste and Emergency Response
PCBs	poly chlorinated biphenyls
ppb	parts per billion
ppm	parts per million
PVC	poly vinyl chloride
R	well bore radius
redox	reducing-oxidising potential
RRMC	Royal Roads Military College
SO_4^{2-}	sulfate ion
SOM	soil organic matter
SPT	standard penetration test
SRB	sulfate-reducing bacteria
1,1,1-TCA	1,1,1-trichloroethane
TCE	1,1,1-trichloroethene
TDS	total dissolved solids
TEAP	terminal electron acceptor processes
TEAs	terminal electron acceptors
TOC	total organic carbon
US EPA	United States Environmental Protection Agency
USCS	Unified Soil Classifications System

ABBREVIATIONS (continued)

VC	vinyl chloride
VOCs	volatile organic compounds
µs	micro-siemens

1.0 INTRODUCTION

1.1 Problem Statement

An inactive waste disposal facility (landfill) exists at 4 Wing Cold Lake in Cold Lake, Alberta and is known to be leaching elevated concentrations of organic contaminants. There has been a concern that these contaminants may eventually migrate into a nearby creek, although evidence to date is that no measurable contaminants have travelled that far. The contaminants of concern have been identified to be primarily chlorinated aliphatic hydrocarbons (CAH) combined with benzene, toluene, ethylbenzene and xylenes (BTEX). Most of these contaminants appeared to be present within a surface aquifer, however it was not certain whether they existed solely in the upper aquifer or had migrated to the lower one as well. As a result, there was a requirement for a study that would:

- Delineate the nature, extent and impact of the landfill contamination;
- Examine the viability of intrinsic bioremediation as a remediation strategy for the site; and
- Determine the risk, if any, that the contaminant plume may present to the identified receptors.

This thesis describes the field and laboratory investigation as well as analytical fate and transport modelling results carried out to meet the above requirements, and the screening criteria required to prove intrinsic bioremediation. The results of the investigation are summarised and recommendations are made regarding the viability of intrinsic bioremediation for this site.

2.0 INTRINSIC BIOREMEDIATION LITERATURE REVIEW

Intrinsic bioremediation (IB) is a component of monitored natural attenuation (MNA), and can be defined as the process of biological degradation of hazardous chemicals such as petroleum hydrocarbons by

indigenous microorganisms, without the control or manipulation of microbial processes in the subsurface, (in situ treatment). The United States Environmental Protection Agency (US EPA) defines MNA as:

...the reliance on natural attenuation processes...to achieve site-specific remedial objectives within a time frame that is reasonable compared to other methods. The processes that are at work...include a variety of physical , chemical, or biological processes that, under favourable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in the soil and groundwater. These in-situ processes include biodegradation, dispersion, dilution, sorption, volatilisation, and chemical or biological stabilisation, transformation, or destruction of contaminants.

In comparison to engineered remediation technologies, intrinsic bioremediation has the following advantages and limitations:

Advantages

1. During intrinsic bioremediation, contaminants are ultimately transformed to innocuous by-products, (i.e. carbon dioxide, or ethene or water);
2. The use of intrinsic bioremediation will reduce the volume of contaminated soil and water wastes and therefore reduce the possibilities of cross-contamination commonly associated with ex-situ treatment;
3. It is non-intrusive and allows continuing use of infrastructure during remediation;
4. Those compounds that are the most mobile and toxic are generally the most susceptible to biodegradation;
5. It eliminates the waste permanently, rather than transporting it elsewhere for further treatment;
6. Intrinsic bioremediation can be used in conjunction with or as a follow-up to other remedial measures;
7. Natural attenuation is not subject to the limitations or capital costs of mechanised remediation equipment (i.e. no equipment downtime); and
8. It requires lower overall remediation costs than those associated with active remediation.

Potential Limitations (OSWER, 1997)

1. Longer time frames may be required to achieve remediation objectives, compared to active remediation;
2. Site characterisation may be more complex and costly;
3. Toxicity and solubility of transformation products may exceed that of the parent compound;
4. Long-term monitoring will generally be necessary;
5. Institutional controls may be necessary to ensure long-term protection;
6. Potential exists for continued contamination migration, and/or cross-media transfer of contaminants;
7. Hydrologic and geochemical conditions amenable to natural attenuation are likely to change over time and could result in renewed mobility of previously stabilised contaminants, adversely impacting remedial effectiveness; and
8. More extensive education and outreach efforts may be required in order to gain public acceptance of monitored natural attenuation.

2.1 Anaerobic Intrinsic Bioremediation

Biodegradation of fuel hydrocarbons, especially benzene, toluene, ethylbenzene and xylenes (BTEX), are primarily limited by electron acceptor availability, and generally will proceed preferentially under aerobic conditions (oxygen being the electron acceptor). However, within the last decade it has become apparent that BTEX can be degraded in an anaerobic (absence of oxygen) environment as well (Lovley, 1997). In an anaerobic environment, microorganisms use electron acceptors other than oxygen during respiration (ElFantroussi et al., 1998). These other electron accepting processes involve manganese (Mn^{4+}), nitrate (NO_3^-), sulfate (SO_4^{2-}), ferric iron (Fe^{3+}) and carbon dioxide (CO_2, i.e. methanogenesis). Of these electron acceptors, Fe^{3+} typically provides the greatest potential electron-accepting capacity in shallow aquifers (Lovley, 1997). However, it is possible that nitrate and sulfate reduction can also be important in BTEX degradation. Furthermore, some BTEX components can be degraded under methanogenic conditions. The

reduction of nitrate, ferric iron or sulfate as well as methanogenesis is referred to as terminal electron accepting processes (TEAPs). These are further discussed in Section 2.3.

In relation to the landfill site, the instantaneous amount of oxygen required for toluene to be fully biodegraded through aerobic respiration can be estimated from the following:

Equation 1: Aerobic Degradation of Toluene

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$$

Given toluene's density (0.867 g/mL), molecular weight (94 mg/mmol) and in-situ concentration (~ 30 mg/L) the amount of oxygen required to degrade a specific amount of toluene in groundwater can be estimated. Assuming a volume of 1L of groundwater at a concentration of 30 mg/L, 96 mg/L of oxygen would be required, which is higher than its solubility limit (approximately 9 mg/L). The total BTEX concentration in the groundwater is approximately 50 mg/L, therefore it can be reasonably assumed that BTEX degradation will be anaerobic at the site since dissolved oxygen (DO) levels in the plume are less than 0.5 mg/L.

In contrast to BTEX compounds, the more highly chlorinated hydrocarbons such as tetrachloroethene (or perchlolorethene), trichloroethene (TCE) and trichloroethane (TCA) are typically biodegraded *only* under anaerobic conditions (Lee et al., 1998). As a result of these findings, anaerobic bioremediation has been gaining acceptance as a viable means for treating soils contaminated with the more highly chlorinated aliphatic compounds (CAH).

2.2 Intrinsic Bioremediation of Chlorinated Hydrocarbons: Reductive Dechlorination

To degrade chlorinated hydrocarbons in-situ and anaerobically, the following conditions must be present or enhanced:

1. A microbial population capable of degrading the chlorinated hydrocarbons (Lee et al., 1998);
   This is rarely a limiting factor as there are many species of microorganisms capable of degrading organic compounds and these are found in many different environments (Borden et al., 1994).
2. Contaminant concentrations must be within an acceptable range that the microorganisms can degrade;
3. Structure and characteristics of the target pollutants must be suitable for microbial degradation;
   Some organic molecules resist degradation due to their large size or type of functional groups. Strong sorption onto aquifer material can also hinder the ability of bacteria to attach to, absorb, or enzymatically attack the molecule (Godsy, 1994);
4. An appropriate electron donor, or substrate, must be available to achieve reducing conditions in the aquifer and to meet the demand for cell growth and metabolism.
   This could be in the form of indigenous carbon, anthropogenic carbon, or other inorganic substances such as hydrogen (H_2) or ammonia (NH_4^+);
5. For this type of reaction to be thermodynamically favourable, the redox potential must be very low, thereby excluding the presence of dissolved oxygen (i.e. < 0.5 mg/L);
6. Toxic substances such as heavy metals that can limit microbial growth rates, must be absent; and
7. Requisite nutrients must be available, and environmental conditions must be favourable (i.e. appropriate pH and temperature). The major limiting nutrients for growth are nitrogen and phosphorus although sulfur, calcium, magnesium, and trace metals are also required, and if not present in adequate supply, will hinder cell growth. Near neutral pH values are usually optimum for the biodegradation of organic material. The effects of temperature on biodegradation are complex, but generally the rate of enzymatic degradation and bacterial metabolism double for every 10°C increase, (also known as the Q_{10} rule).

There are three different circumstances under which chlorinated hydrocarbons will undergo biodegradation:

1. Microbial use as an electron acceptor;
2. Microbial use as an electron donor; or
3. Through cometabolism where degradation of the chlorinated organic is fortuitous and there is no benefit to the organism (McCarty, 1996).

These processes are discussed individually in the following sections.

2.2.1 Electron Acceptor Reactions – Reductive Dechlorination

The most important process for natural biodegradation of the more highly chlorinated solvents is *reductive dechlorination*, a process that requires both electron acceptors (the CAH) and an adequate supply of electron donors. Electron donors include fuel hydrocarbons or other types of anthropogenic carbon (i.e. landfill leachate) or natural organic carbon. If the subsurface environment is depleted of electron donors before the CAH are removed, biological reductive dechlorination of the most highly chlorinated compounds will cease (Wiedemeier et al., 1998).

During the process of reductive dechlorination, the chlorinated hydrocarbon is used as an electron acceptor, and a chlorine atom is removed and replaced with a hydrogen atom. Figure 1 illustrates the transformation of 1,1,1-trichloroethane (TCA) via reductive dechlorination. This process is associated with the accumulation of daughter products (compounds into which the initial contaminant is subsequently broken down), and an increase in the concentration of chloride ions in the groundwater (Lee et al., 1998).

Reductive dechlorination affects each of the chlorinated ethanes differently. Compounds that are more highly oxidised (i.e. TCA) are more susceptible to dechlorination than compounds that are less oxidised (vinyl chloride – VC). As a result the rate of reductive dechlorination decreases as the degree of chlorination decreases (Vogel and McCarty, 1985; Bouwer, 1994).

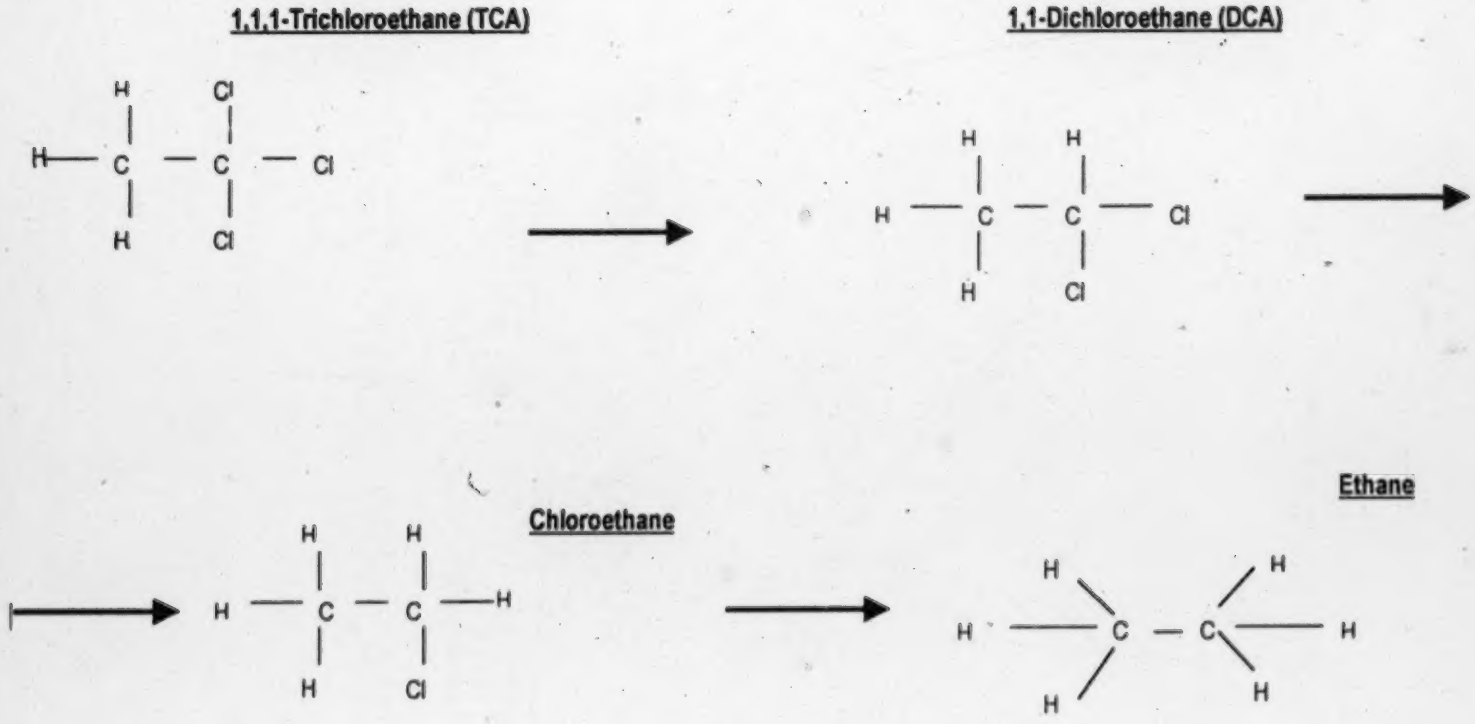


Figure 1: Reductive Dechlorination of 1,1,1-Trichloroethane (Adapted from Wiedemeier et al., 1998; McCarty, 1996)

2.2.2 Electron Donor Reactions

In this type of reaction, the less oxidised CAH (i.e. VC), can be used as the primary substrate or electron donor, in biologically mediated redox-reactions (McCarty and Semprini, 1994). During electron donor reactions, the facilitating microorganism obtains energy and organic carbon from the degraded chlorinated hydrocarbon. In contrast to reactions where the CAH is used as an electron acceptor (reductive dechlorination) only the least oxidised CAHs can be used as electron donors (Wiedemeier et al., 1998). McCarty and Semprini (1994) described laboratory investigations where VC and 1,2-dichloroethane (DCA) served as primary substrates under aerobic conditions. They also documented the potential of dichloromethane to function as a primary substrate under either aerobic or anaerobic conditions.

2.2.3 Cometabolism

During cometabolism, degradation is catalysed by an enzyme or cofactor that is fortuitously produced by organisms for other purposes (Wiedemeier et al., 1998). The reactions carried out by the microorganisms are not thought to be energy-yielding but rather cometabolic because only a small fraction of the total reducing equivalents derived from the oxidation of electron donors is used to reduce the chlorinated compound (Lee et al., 1998). In other words, bacteria indirectly transform the chlorinated compound as they use other substrates to meet their energy requirements. Therefore, the chlorinated compound does not enhance the degradation of the substrate (i.e. BTEX or other carbon sources), nor will its cometabolism interfere with the use of electron acceptors involved in the oxidation of those carbon sources. Cometabolism is best documented under aerobic conditions, although it could potentially occur under anaerobic conditions (Wiedemeier et al., 1998).

2.3 Geochemical Processes Affecting Reductive Dechlorination

To adequately determine the amount and three-dimensional distribution of dissolved contamination and to document the occurrence of natural attenuation, groundwater samples must be obtained and analysed for both contaminant concentrations and geochemistry. It is known that a thorough assessment of the geochemical parameters can be used to delineate the contaminant plume and indicate the significant chemical/biological reactions that are occurring. It is therefore necessary to understand the TEAPs that are taking place in the plume.

The TEAPs can be best described through oxidation-reduction potential (ORP). The ORP of groundwater is a measure of electron activity and an indicator of the relative tendency of a solution to accept or transfer electrons (Appelo and Postma, 1996). During this process the organic matter acts as an electron donor and different compounds are used as the electron acceptor. Microorganisms that gain energy required for cell growth from the process mediate the ORP reaction. Of all oxidants, oxygen has the highest molecular energy yield (Figure 2). Each successive TEAP provides decreasing energy to the microorganisms, which generally results in a lower magnitude and rate of degradation, (see Figure 2). The anaerobic TEAPs are also generally segregated into distinct zones in aquifers that are contaminated with organic matter, (Figure 3).

2.3.1 Dissolved Oxygen (DO)

Dissolved oxygen is the electron acceptor most thermodynamically favoured by microbes for the biodegradation of organic carbon, whether natural or anthropogenic. However, reductive dechlorination will not occur if DO concentrations are above approximately 0.5 mg/L (Wiedemeier et al., 1998). During aerobic biodegradation of a substrate, DO concentrations decrease because of the microbial oxygen demand. The extent of aerobic degradation is controlled by the amount of contaminant released, the rate of oxygen recharge, and the background oxygen content in the groundwater (Borden et al., 1994).

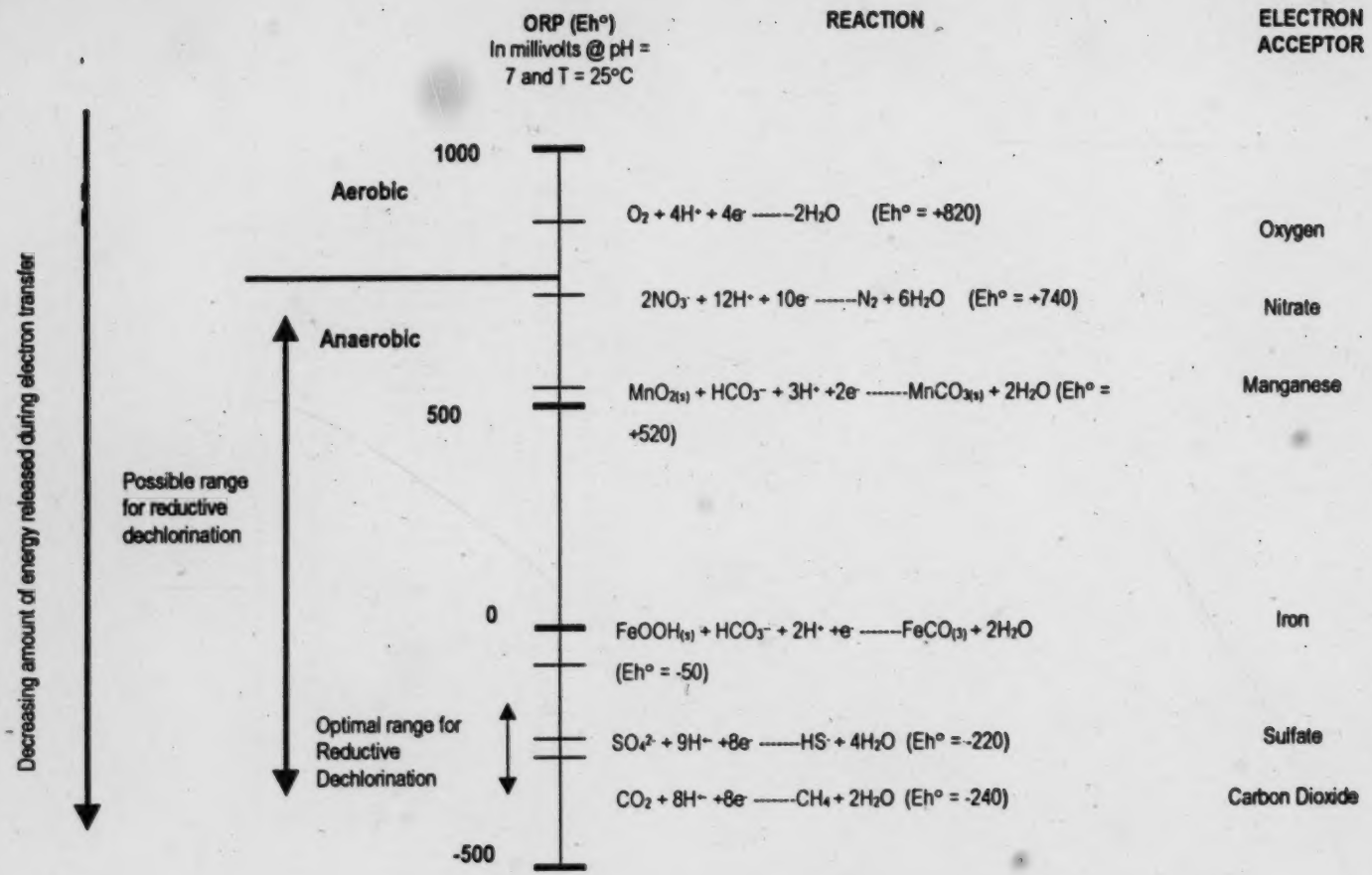

ORP (Eh°)
In millivolts @ pH = 7 and T = 25°C
REACTION
ELECTRON ACCEPTOR
1000
Aerobic
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (Eh° = +820)
Oxygen
$2NO_3^- + 12H^+ + 10e^- \rightarrow N_2 + 6H_2O$ (Eh° = +740)
Nitrate
Anaerobic
$MnO_{2(s)} + HCO_3^- + 3H^+ + 2e^- \rightarrow MnCO_{3(s)} + 2H_2O$ (Eh° = +520)
Manganese
500
Possible range for reductive dechlorination
0
$FeOOH_{(s)} + HCO_3^- + 2H^+ + e^- \rightarrow FeCO_{(3)} + 2H_2O$ (Eh° = -50)
Iron
Optimal range for Reductive Dechlorination
$SO_4^{2-} + 9H^+ + 8e^- \rightarrow HS^- + 4H_2O$ (Eh° = -220)
Sulfate
$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$ (Eh° = -240)
Carbon Dioxide
-500
Decreasing amount of energy released during electron transfer

Figure 2: Redox Potentials for Various Electron Acceptors (Modified from Appelo and Postma, 1996; Bouwer, 1994).

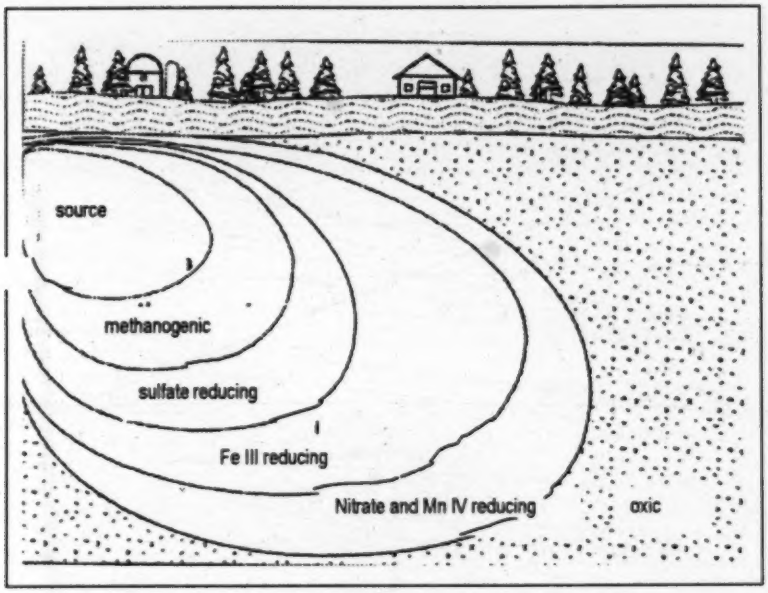


Figure 3: Typical Distribution of Anaerobic TEAPs in a Contaminated Aquifer (redrawn from Lovley, 1997).

2.3.2 Nitrate (NO_3^-)

After dissolved oxygen depletion, only anaerobic microbes that can, will use nitrate as an electron acceptor. Nitrate has an energy yield somewhat less than to that of dissolved oxygen, and is primarily reduced to nitrite (NO_2^-) and eventually to nitrogen gas (N_2). Most heterotrophic denitrifiers (microorganisms that use nitrate as an energy source) found in aquifers are facultatively anaerobic. This means the microbes can switch from using molecular oxygen to using nitrate as a terminal electron acceptor (Kinzelbach et al., 1991).

2.3.3 Iron III (Fe^{3+})

Once nitrate has been depleted, iron (III) or ferric iron can be used as an electron acceptor. Generally, Fe^{3+} is the most abundant potential electron acceptor for organic matter degradation in groundwater (Lovley, 1997). Fe^{3+} is insoluble, but when reduced to Fe^{2+} (ferrous iron) it is soluble

and can be used as an indicator of iron reduction. When oxygen and nitrate have been consumed, microorganisms such as *Geobacter metallireducens* can use ferric iron as an electron acceptor.

2.3.4 Sulfate (SO_4^{2-})

After nitrate and iron depletion occurs in the microbiological treatment zone, sulfate (SO_4^{2-}) may be used as an electron acceptor for anaerobic degradation. Sulfate reducing conditions, where sulfide is produced as an end product, is one of two TEAPs where chlorinated aliphatic hydrocarbons are most readily degraded. The process is not well quantified, but usually occurs near the centre of the plume, farthest from the surrounding uncontaminated (aerobic) groundwater (Corseuil and Alvarez, 1996). This general observation is due to the fact that aerobic conditions are toxic to sulfate-reducing bacteria, (SRB).

2.3.5 Carbon Dioxide (CO_2)

The final terminal electron process is methanogenesis, where acetate is split to form carbon dioxide (CO_2) and methane (CH_4), or carbon dioxide is used as an electron acceptor and is reduced to methane (Appelo and Postma, 1996). It is clear, from the oxidation-reduction reaction for methane, that it is not very thermodynamically favourable. Therefore, methanogenesis generally occurs after oxygen, nitrate, iron and sulfate have all been depleted in the treatment zone. The presence of methane in groundwater is indicative of strongly reducing conditions (Appelo and Postma, 1996). Since methane is not present in liquid fuels, the presence of methane above background concentrations in groundwater that is in contact with fuels is indicative of microbial degradation of hydrocarbons (Chapelle, 1993).

2.4 Behaviour of Chlorinated Solvent Plumes

According to Wiedemeier et al. (1998), chlorinated solvent plumes can exhibit three different types of behaviour depending on:

- the amount of solvent;
- the amount of biologically available organic carbon in the aquifer;
- the distribution and concentration of natural electron acceptors; and
- the types of electron acceptors being used.

It is also possible for individual plumes to exhibit all three types of behaviour in different portions of the plume.

2.4.1 Type 1 Behaviour

Type 1 behaviour occurs when the primary substrate is anthropogenic carbon, (i.e. BTEX or landfill leachate), and microbial degradation of the anthropogenic carbon drives reductive dechlorination.

2.4.2 Type 2 Behaviour

Type 2 behaviour dominates in areas that are characterised by relatively high concentrations of biologically available native organic carbon (Wiedemeier et al., 1998). It is the microbial utilisation of the natural carbon source that drives reductive dechlorination. Type 2 behaviour usually results in slower biodegradation than Type 1 behaviour. However, under the right conditions, such as areas with high natural organic carbon contents, Type 2 behaviour can also result in rapid degradation of CAHs.

2.4.3 Type 3 Behaviour

Type 3 behaviour is exhibited where there are inadequate concentrations of native and/or anthropogenic carbon, coupled with dissolved oxygen concentrations of greater than 1.0 mg/L. Under these aerobic conditions, reductive dechlorination will not occur. The most significant natural attenuation mechanisms will be advection, dispersion and sorption. However, VC can be rapidly oxidised under these conditions. This type of behaviour can also occur in groundwater that does not contain microorganisms capable of biodegradation of chlorinated solvents.

2.5 Lines of Evidence Required for Intrinsic Bioremediation

To support intrinsic bioremediation the proponent must scientifically demonstrate that attenuation of the site contaminants is occurring at rates sufficient to be protective of human health and the environment. There are three accepted lines of evidence that can be used to support natural attenuation of chlorinated aliphatic hydrocarbons. They are as follows (Wiedemeier et al., 1998):

1. Observed reductions in contaminant concentrations along the flow path downgradient from the source of contamination;
2. Documented loss of contaminant mass at the field scale using:
   a) Chemical and geochemical analytical data including:
      - Decreasing parent compound concentrations;
      - Increasing daughter compound concentrations;
      - Depletion of electron acceptors and donors; and
      - Increasing metabolic by-product concentrations.
   b) A conservative tracer and rigorous estimate of residence time along the flow path to document contaminant mass reduction and to calculate biological decay rates at the field scale;
3. Microbiological laboratory or field data that support the occurrence of biodegradation and give rates of biodegradation.

The US EPA recommends that at a minimum, the investigator must obtain the first two lines of evidence or the first and the third lines of evidence. Either the second or the third line of evidence is imperative to the natural attenuation demonstration because they provide biodegradation rate constants. These rate constants are subsequently used in conjunction with the other fate and transport parameters to predict contaminant concentrations and to assess risk (if any) at downgradient points of compliance.

2.6 Intrinsic Bioremediation Screening Process

In order to prove the previously mentioned lines of evidence and therefore produce an accurate assessment of the potential for intrinsic bioremediation of chlorinated hydrocarbons, Wiedemeier et al. (1998) suggest that a detailed screening process be carried out. This initial screening process is designed to recognise the geochemical environments where reductive dechlorination is possible, since it is through this process that CAHs will most readily biodegrade. The recommended screening process requires the following information:

- Chemical and geochemical data for background and target areas of the plume (Figure 4);
- Locations of source(s) and potential points of exposure and, where non-aqueous phase liquid (NAPL) exists as a source and an estimate of the extent of residual and free-phase is required; and
- An estimate of the transport velocity and direction of groundwater flow.

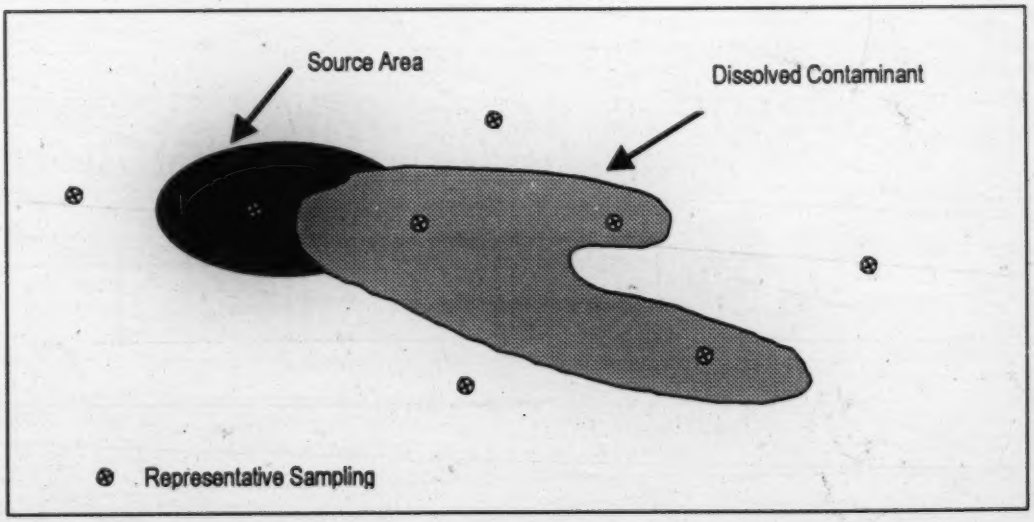


Figure 4: Suggested Target Locations for Collecting Screening Data (Adapted from Wiedemeier et al., 1998).

Once these data have been collected, the screening process can be undertaken. The following steps summarise the screening process as identified by Wiedemeier et al., (1998):

1. Determine if biodegradation is occurring using geochemical data; if it is proceed to step 2;
2. Determine groundwater flow and solute transport parameters from representative field data;
3. Locate source(s) and potential points of exposure; if NAPLs are sources, estimate extent of residual and free-phase NAPL;
4. Estimate the biodegradation rate constant;
5. Compare rate of transport to the rate of attenuation; and
6. Determine whether screening criteria are met.

3.0 PROBLEM DEFINITION

3.1 Site Description and Layout

4 Wing Cold Lake is situated close to the community of Cold Lake, approximately 300km north-east of Edmonton, and 10km west of the Alberta – Saskatchewan border. Geographically, the region is classified as the Beaver Lowlands and is characterised by flat to rolling glacially streamlined terrain. Regional topography is dominated by rolling hills and undulating plains. There is virtually no bedrock outcrop in the area. The subcropping bedrock formations include the Wapiti and Lea Park units of sandstone, mudstone and shale in the Upper Cretaceous age. Surficial groundwater movement occurs mainly within the glaciofluvial, alluvial and granular drifts of the till layer (Ozoray, et al. 1979).

The former landfill site is located on the north side of the Base (Figure 5), bordered on the south-west by a runway, and on the north-east by the Marie Creek valley. Its size is estimated as 450 x 1100m from an aerial photograph taken in 1955, which appears to have been at the height of waste disposal activity.

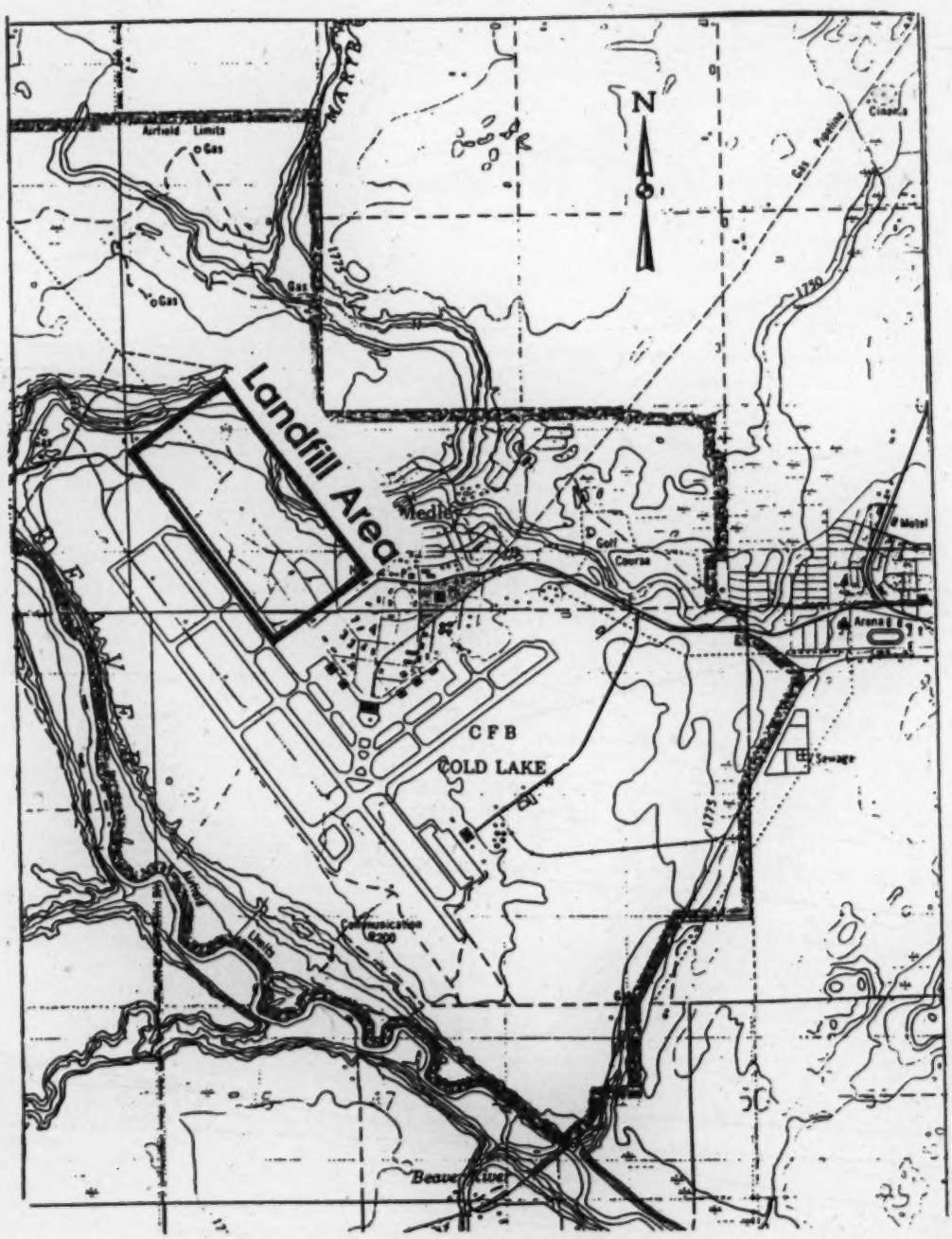


Figure 5: Plan of Area from1:50,000 Topographic Map

There are no written records available to indicate what types of material were disposed of, however review of old reports and interviews with Base personnel indicate that at one point the site was used as the principle waste disposal area for CFB Cold Lake. Some of the more recent waste disposal activities have signs indicating what they were. These include an asbestos burial area, a CF-18 aircraft burial site, and an aircraft tire dump.

From the initial reconnaissance visit coupled with old reports of the site, it was confirmed that the landfill had been filled and levelled. There are medium sized trees (spruce and poplar) growing throughout the area. Also visible are several gravel roads within the site, well-trodden paths and cut lines to the north-east of the landfill. A buried storm sewer outfall (300m long, ~ 30cm diameter) borders the south-east edge of the landfill. It carries the drainage from the runway, and flows into a levelled drainage ditch for approximately 100m, then by a natural slope leading to Marie Creek. These features are indicated on Figure 6, which has been generated from aerial photographs and drawings from previous studies.

Overall, the area is quite flat although the Marie Creek valley is somewhat steep. To the east of the landfill and south of Marie Creek is a gently sloping bog characterised by sphagnum beds and low lying shrubs and evergreens. The bog is approximately 40m in length (from the drainage ditch towards Marie Creek) and 50m in width. The drainage ditch from the storm sewer outfall extends approximately 10m into this area. At the end of the ditch the flow pattern is not apparent. Instead, the ditch discharge seems to spread out and seeps, rather than flows, through the bog. There are two depressions on either side of the bog that appear to drain into it. It should be noted that the volume of water flowing into these depressions is very low. The low-lying vegetation of the bog seems not only to retard the flow of water, but to act as a barrier to the movement of organic contaminants, as reported in the RRMC report (1991).

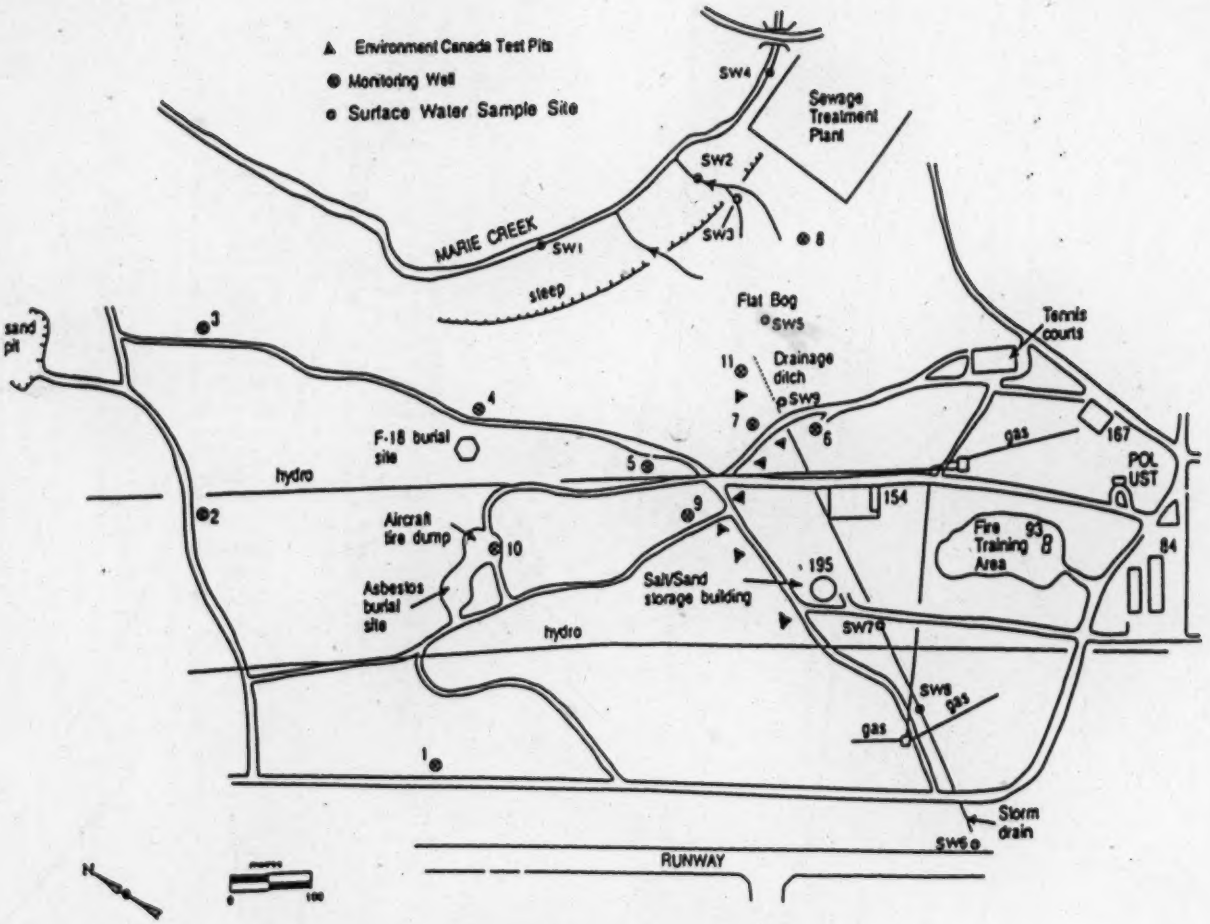


Figure 6: Plan View Old Landfill Area at CFB Cold Lake

3.2 Possible Risk to Receptors

There are two possible environmental risks to receptors for this site. First, there is concern that the identified contaminants will be introduced into Marie Creek, which flows into the Beaver River. Secondly, there is risk of contaminant uptake by vegetation in the area that could subsequently enter the food chain. At present there are no drinking water wells in the vicinity, thus reducing the risk to humans through direct consumption.

3.3 Previous Studies

3.3.1 1 Construction Engineering Unit (1 CEU) Report

In 1988 a hydrocarbon sheen was observed floating on the water surface in the drainage ditch near the storm sewer outfall, and in the boggy area immediately north of it (Figure 7). It appeared that the contamination was not originating from the sewer itself, but instead was leaching from around it, and from the banks of the drainage ditch. As a result, Environment Canada was apprised of the situation and conducted an initial investigation. Seven test pits were dug in the vicinity of the drainage ditch, and water, soil and sediment samples were collected, (Figure 6). Analysis of these samples confirmed the presence of hydrocarbons and showed that no poly chlorinated biphenyls (PCBs) or organochlorine pesticides existed. Water samples obtained from Marie Creek were found to be uncontaminated.

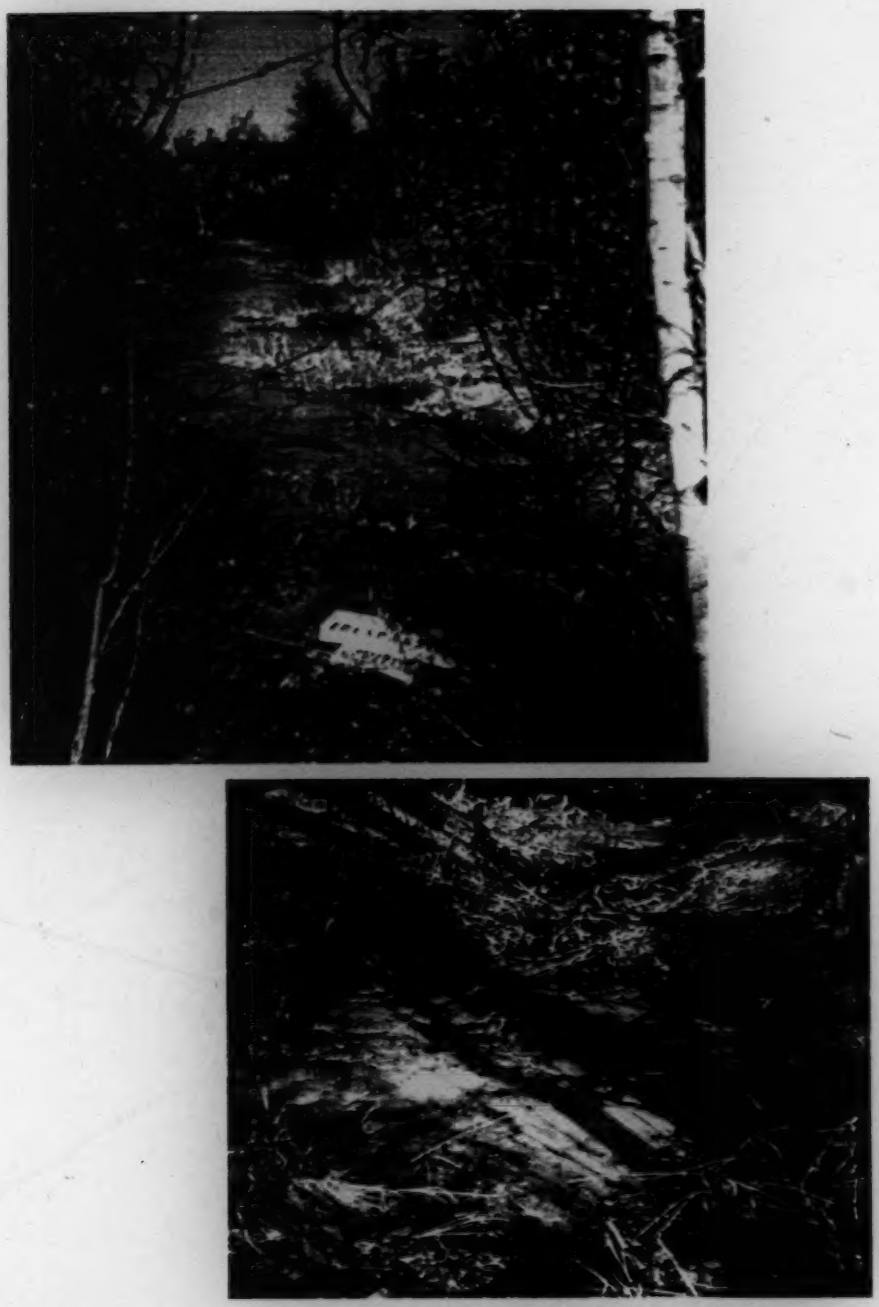


Figure 7: a) Photograph of Drainage Ditch Below Sewer Outfall b) Photograph of Hydrocarbon Spreading from Ditch

In 1989 1 CEU, a Department of National Defence (DND) agency, was asked to undertake a more detailed study. This included characterisation of the hydrogeology, evaluation of the groundwater contamination and its impact, and a preliminary estimate of the nature and scope of remedial measures. The field work took place in two phases (August 8 – 18, 1989 and October 2 – 4, 1989). This included the drilling of boreholes and the installation of 11 monitoring wells, as well as the collection of surface and subsurface soil and water samples. The locations of the monitoring wells installed by 1 CEU are shown on Figure 6.

The waste disposal site is characterised by two distinct aquifers with groundwater conditions particular to each one. The upper layer is a moderately permeable sand layer underlain by very impermeable clay. The1 CEU report indicated that the groundwater flowed in a north-easterly direction, and appeared to surface in the boggy area near well 11. The lower aquifer is a sand layer starting at a depth of approximately 7m, but the vertical extent of this layer was not determined. The findings of 1 CEU are consistent with the geological characteristics reported by Andriashek and Fenton, (1989). The geologic section shown in Figure 8 (Andriashek and Fenton, 1989) would predict a single aquifer in the upper glaciofluvial sediments, with the underlying clay-till (Grand Centre formation) acting as an aquitard. Sand lenses of various sizes have been noted in this lower clay-till layer. These would contain water, but are expected to be discontinuous (Ozoray et al., 1979).

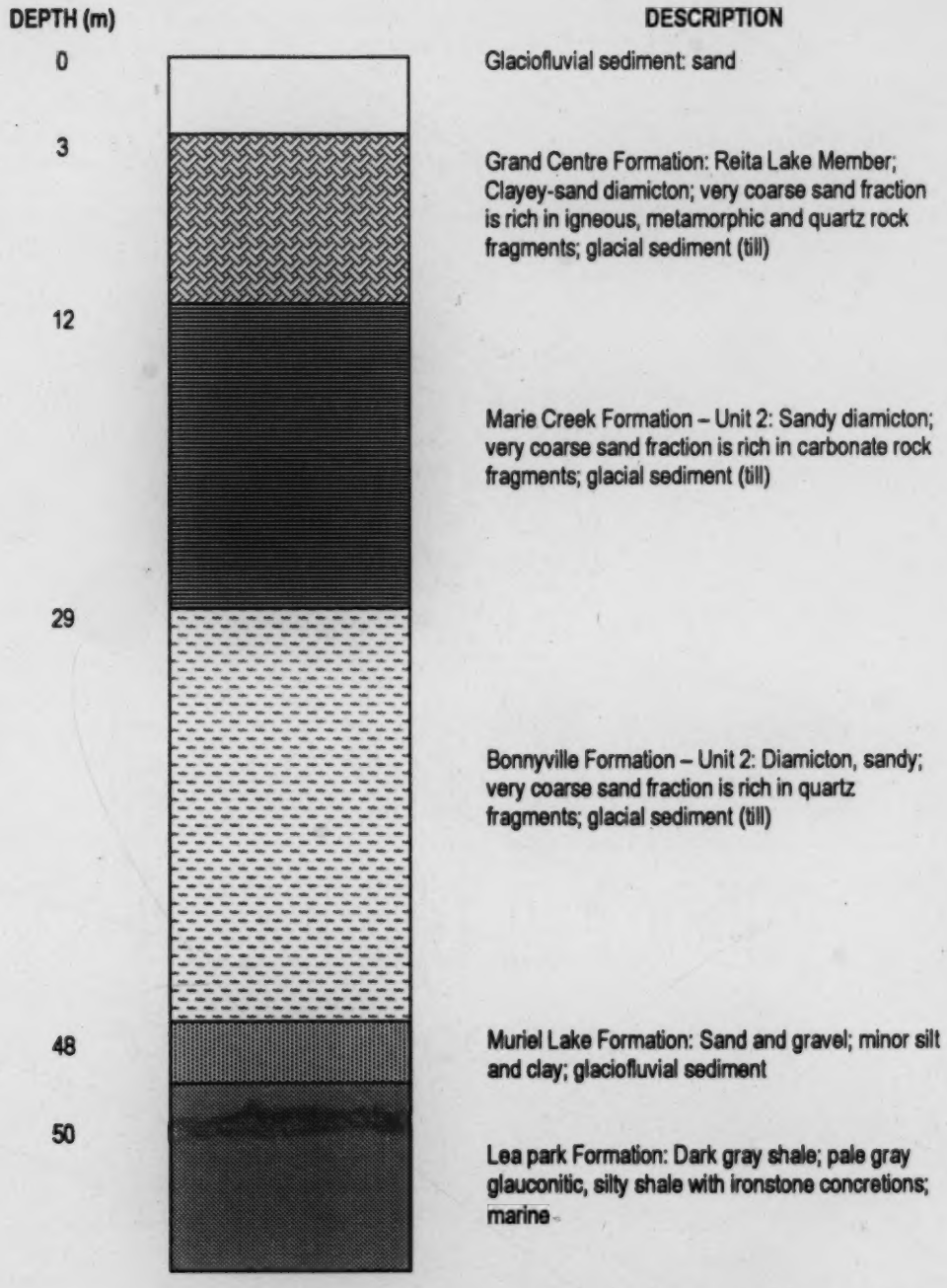

DEPTH (m)
DESCRIPTION
0
Glaciofluvial sediment: sand
3
Grand Centre Formation: Reita Lake Member; Clayey-sand diamicton; very coarse sand fraction is rich in igneous, metamorphic and quartz rock fragments; glacial sediment (till)
12
Marie Creek Formation – Unit 2: Sandy diamicton; very coarse sand fraction is rich in carbonate rock fragments; glacial sediment (till)
29
Bonnyville Formation – Unit 2: Diamicton, sandy; very coarse sand fraction is rich in quartz fragments; glacial sediment (till)
48
Muriel Lake Formation: Sand and gravel; minor silt and clay; glaciofluvial sediment
50
Lea park Formation: Dark gray shale; pale gray glauconitic, silty shale with ironstone concretions; marine

Figure 8: Geological Cross-Section for Landfill (after RRMC, 1991)

Chemical analysis of the samples was quite limited. The results indicated that contamination was localised in the area of the drainage ditch and well 7 (refer to Figure 6). Possible contaminants were identified as "volatile mono cyclic aromatic hydrocarbons, phenolics and aromatic and poly-cyclic hydrocarbons". There was also a suggestion that phosgene was present in low concentrations. A risk assessment concluded that the groundwater, although contaminated, did not pose an immediate risk to human or environmental health. However, there was a concern with the impact of surfacing groundwater in the bog.

Environmental Protection reviewed the 1 CEU report and emphasised the need to take steps to prevent any further migration of contaminants from the site, and to establish a plan for reclamation as soon as feasibly possible. The primary concern was "... the possibility that the bog and forested area between the site and Marie Creek, which is acting as a temporary buffer zone, may reach capacity and/or be circumvented, permitting direct contaminant deposit to Marie Creek and ultimately, the Beaver River" (1 CEU, 1989). In 1991 another DND agency was tasked to further investigate the problem.

3.3.2 Royal Roads Military College (RRMC)

On May 29, 1991 the Royal Roads Military College (RRMC) Environmental Sciences Group was asked by the Deputy Chief of Staff Construction Engineering to conduct an environmental study at the old landfill site at CFB Cold Lake. The purpose of the investigation was twofold:

- To evaluate the environmental impact of the landfill and thereby establish an appropriate remediation program; and
- To train base personnel to monitor the landfill site.

These objectives were met by conducting three field visits. The first was an initial reconnaissance visit where interviews with Base personnel were conducted, water samples from the 1 CEU monitoring wells were taken as well as several surface water samples. These samples were subjected to an extensive set of chemical analyses. The results of these first samples confirmed the observations noted in the 1 CEU report. That is, that the main area of concern was confined to a boggy area at the edge of the landfill, in the vicinity of the runway storm sewer discharge point, where the groundwater surfaces, (refer to Figure 9).

The major contaminants were determined to be organic compounds consistent with the landfilling of lubricants, fuels and degreasers. A review of geological and site maps, as well as historical aerial photographs, suggested a possible source – a pit (no longer visible) that was previously used for waste oil disposal. This oil pit had been located within the landfill in a flat area to the north of the salt/sand storage building (Bldg 195), as indicated on Figure 9.

During the second field visit an electromagnetic induction (EM) survey was conducted. Unfortunately a high conductivity plume (concentrations as high as 10,000 mg/L), caused by the infiltration of salt from Bldg. 195, masked any possibility of delineating the plume accurately. The results however, did provide additional confirmation that the groundwater flow was to the north-east.

The final field investigation focused primarily on the installation of 17 more monitoring wells and their sampling. Surfacing groundwater, water and soil/sediment samples were also collected from shallow pits dug in the bog and below the creek escarpment in the wooded area between the bog and Marie Creek. Elevated levels of several organics contaminants were found in the bog, but no substances of environmental concern were found in the samples collected in Marie Creek, or in surface flowing watercourses between the bog and the creek itself.

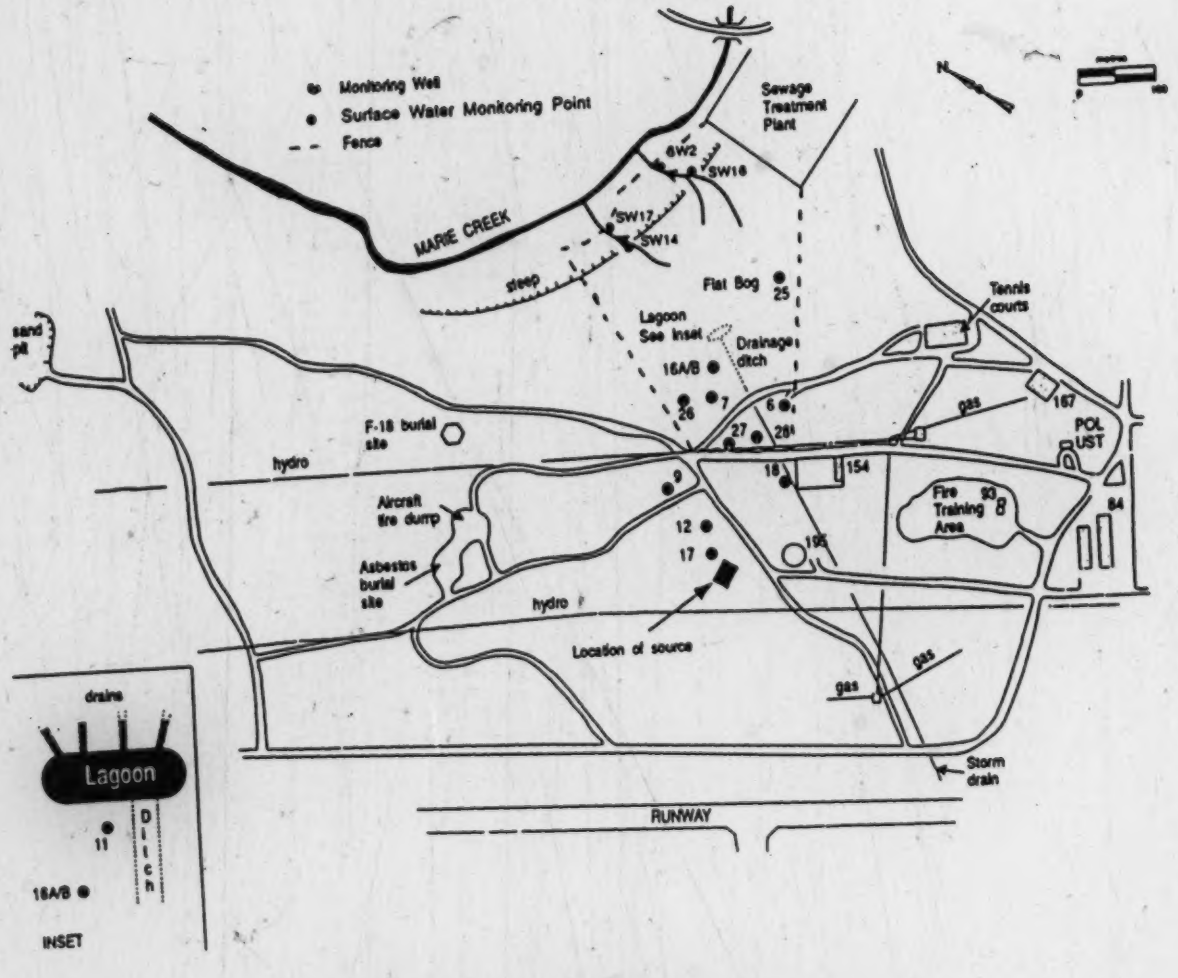


Figure 9: Map Delineating Results of RRMC Study

Several conclusions were presented in the final report. These include:

- The principle compounds of environmental concern were: benzene, toluene, xylenes, ethylbenzene, phenols, 1,1-dichloroethane and 1,1,1-trichloroethane;
- These compounds were reported to be in the groundwater and the surface water in the bog where the groundwater surfaces, however the concentrations were close to typical detection limits (i.e. 0.01 µg/L);
- Contaminant levels in the groundwater plume exceed many of the current (1992) Canadian Council of Ministers of the Environment (CCME) environmental water quality criteria for freshwater aquatic life (Level 1);
- Although groundwater surfacing at the edge of the landfill contains elevated levels of organic compounds (Well 27 and 7, refer to Figure 10), the concentrations are significantly reduced (by a magnitude of 10 or 100) through natural attenuation by the bog;
- The bog is currently acting as an effective barrier, preventing contaminant migration to Marie Creek; and
- The results were consistent with the contamination emanating from a now buried, oil disposal pit.

RRMC recommended that the area of the surface contamination be fenced and posted. In addition to cordoning the area, it was recommended that a lagoon be constructed to receive both surfacing groundwater and the discharge from the drainage ditch, (Figure 9). The outflow from the lagoon would be dispersed over a larger area in the bog. Finally, it was suggested that monitoring of the ground and surface water be continued.

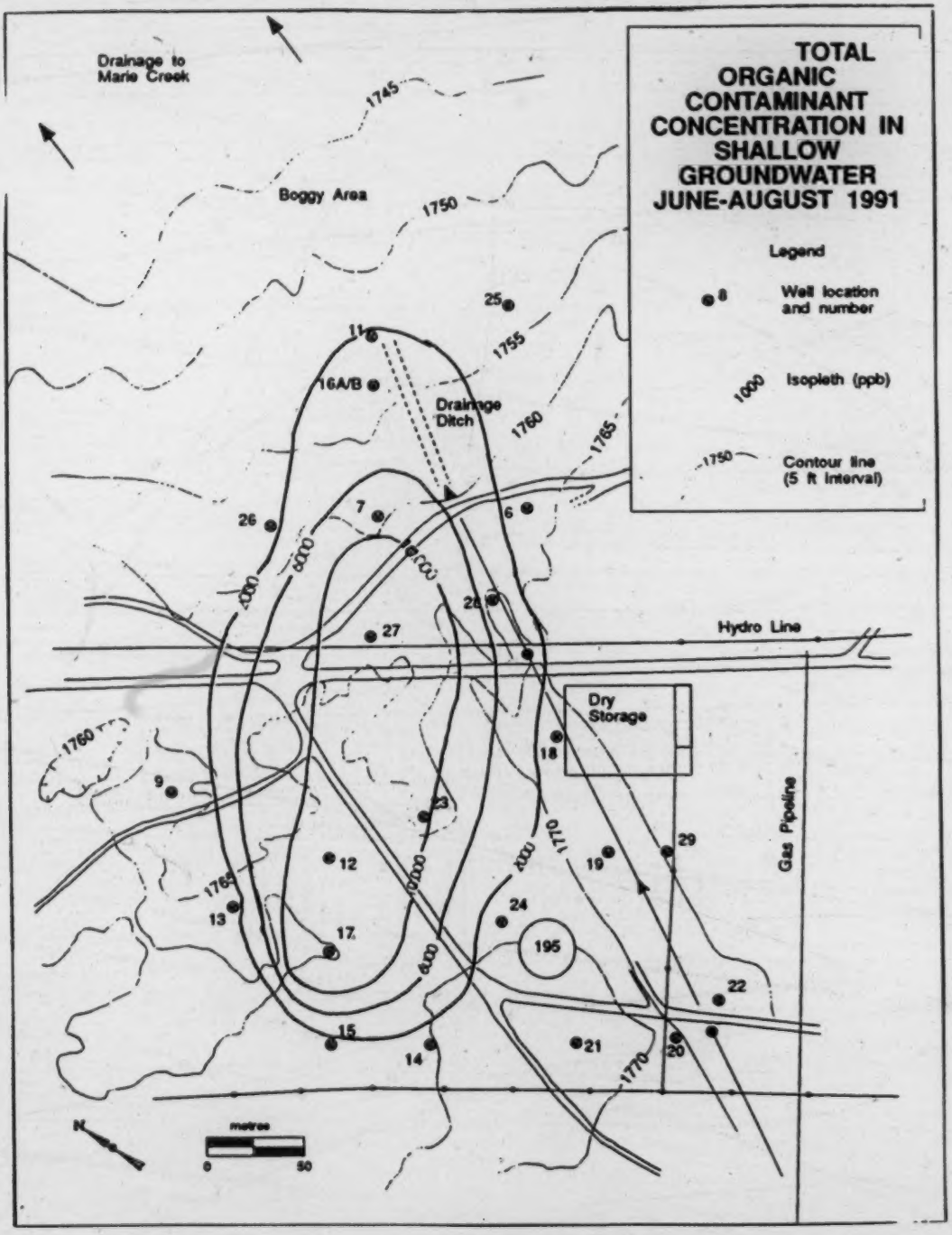


Figure 10: Total Organic Contaminant Concentration in Shallow Groundwater, (Source: RRMC, 1991).

3.3.3 1994 to 1997

Based on the findings of the EM survey in the RRMC report, it was determined that the source of contamination at the landfill site was an old oil pit.

Therefore, the Construction Engineering Environmental Cell excavated three sections (Areas A-C) with a total area of 75 x 32m and an additional section (D) with an area of 16 x 30m, at the end of September 1996 (Pedersen, 1996). The objective of the excavation was to remove the contaminated soil to a depth of 4.5 to 5m, or to the clay, in three separate portions (25 x 32 m). The topsoil was removed in an east to west direction in 8m wide strips, to a depth of 2.0 to 2.5m. The remaining 2.5m of soil was removed only after the top 2.5m had been removed from the site.

Types of materials that were excavated included broken concrete over large bundles of wire and railroad ties, old car parts, pails of roofing tar, hydrocarbon contaminated soil (as indicated by discolouration and soil vapour readings), fuel hoses, crushed drums and pails, two fuel tanks and a large number of aviation fuel filters. Not all of these materials were found in all areas.

Some of the inert materials (such as concrete) were found in Area A. There was however, no contaminated soil found in this area. The boundary of the oil pit was found approximately 8.0m from the west side of Area B. The soil from this area was a black, sandy soil with an obvious hydrocarbon odour (Pedersen, 1996). The contaminated soil started at a depth of 2.0m and extended to the watertable, (approximately 2.5 to 3m). The groundwater beneath the contaminated soil had an oily sheen and a yellow colour. More of the oil pit was found in Area C, which also extended into Area D.

The contaminated soil in Area C started at a depth of 2.0m and extended to the watertable (~2.5m). The groundwater had a hydrocarbon odour and an oily sheen. The yellow discolouration

of the groundwater was more pronounced in this area in comparison to Area B. The excavation at Area D removed the remainder of the contaminated soil, which covered the western half of this area.

In 1995, an orange coloured slime was found in the area adjacent to the drainage ditch, and was subsequently examined microscopically for determining the nature and type of its composition. The examination indicated presence of both bacteria and fungi in a mucilaginous material, but no conclusive microbial identification could be made from the microscopic examination alone (Norwest Laboratories, 1995). Further studies found that the predominant bacteria were *Pseudomonas* sp and *Aeromonas hydrophila*, which are ubiquitous in nature. No further investigation was done in regarding the orange slime.

In 1996 Dr. C. Mendoza, a hydrogeologist from the University of Alberta, was asked to review the existing data regarding the former landfill contamination and provide recommendations for its remediation. The ensuing report (Mendoza, 1996) indicated that the distribution of the dissolved contamination appeared to be sufficiently characterised and was not likely to impact Marie Creek in the near future. He stated however, that it was highly probable that NAPL was still present in the vicinity of the former waste disposal pit. As a result, Dr. Mendoza recommended that the lateral and vertical extent of the NAPL and its composition should be ascertained in order to remediate the source.

Dr. Mendoza recommended that the extent of a light non-aqueous phase liquid (LNAPL) plume be better delineated. The recommended methods, (in approximate order in which they should be attempted), were: airphoto interpretation, a ground-penetrating radar survey, a soil-gas survey and subsurface sampling using cone penetrometers and/or multi-level piezometers. He also added that

the groundwater and soil samples should be subjected to the most sensitive chemical analyses possible in order to detect trace amounts of the less soluble constituents of the NAPL.

After the NAPL source had been remediated, Dr. Mendoza suggested that representative values for the organic content or the distribution coefficients should be determined for both the aquifer and the boggy area. These values would assist in estimating mass migration rates for assessing plume clean-up. Lastly, although it wasn't fully detailed in his review, Dr. Mendoza stated that the source of the chloride plume (Bldg. 195) should be removed since the chloride concentrations in the groundwater were significantly higher than drinking water standards, and the chloride plume could disperse over time.

From December 14 to 19, 1997 IWR Technologies Ltd. (IWR) mobilised and installed a multi-phase vacuum extraction system that would process the contaminated groundwater from wells 28, 27, 204 and 18, (refer to Figure 12). Their report (IWR, 1997) stated that the produced groundwater was passed through a separator, and then through two vessels containing activated carbon. As a final polishing treatment, the water was then passed through organic clay prior to being discharged to the bog. The system operated normally from January, 1998 to mid-March, 1998.

During the month of January, Defence Construction Canada (DCC) ordered an analysis of the effluent for TCA and DCA. The results were received February 19, 1998 and were 207µg/L for DCA and 113µg/L for TCA (nearly 100 times greater than discharge requirements). These results prompted the system to be shut down since the contaminant level of the compounds was too high for straight discharge into the bog. Both DCC and IWR discussed alternatives, but ultimately it was decided to shut down the system and demobilise. At this time 65,970L of water had been "treated" and discharged and 35L of free product had been recovered and collected in the separator.

Prior to the pump and treat project, base personnel in the Construction Engineering Environment Cell decided to investigate the use of a funnel and gate reactive barrier as a remedial option. An area approximately 200m in length was designated for the study, (refer to Figure 11). An-Geo Environmental Consultants Ltd. (An-Geo) were tasked to determine the design parameters for a funnel and gate system for the contaminated area.

3.3.4 An-Geo Environmental Consultants Ltd. (An-Geo)

An-Geo were hired in 1997 to further investigate the former landfill site. The objective of the study was to characterise the stratigraphy and groundwater behaviour in the area designated for the funnel and gate system. This was carried out by installing 12 monitoring wells and sampling 14 of the existing wells, (Figure 11). Permeability tests were also conducted. No chemical analysis was done at this time.

From the information gathered during An-Geo's study, it was concluded that a funnel and gate system would not be feasible. The reasons for its impracticality were:

1. The groundwater flow across the study area was too high (1×10^{-4} m^3sec per metre width). It was also assumed that spring flow would be more abundant;
2. The vertical variation of the watertable over time was significant and there was lack of data to define the flow fluctuation; and
3. Free-phase light non-aqueous phase liquids (LNAPL) was detected atop the groundwater table, where it had not been previously detected (refer to Figure 11), and which was outside of the designated area for the funnel and gate.

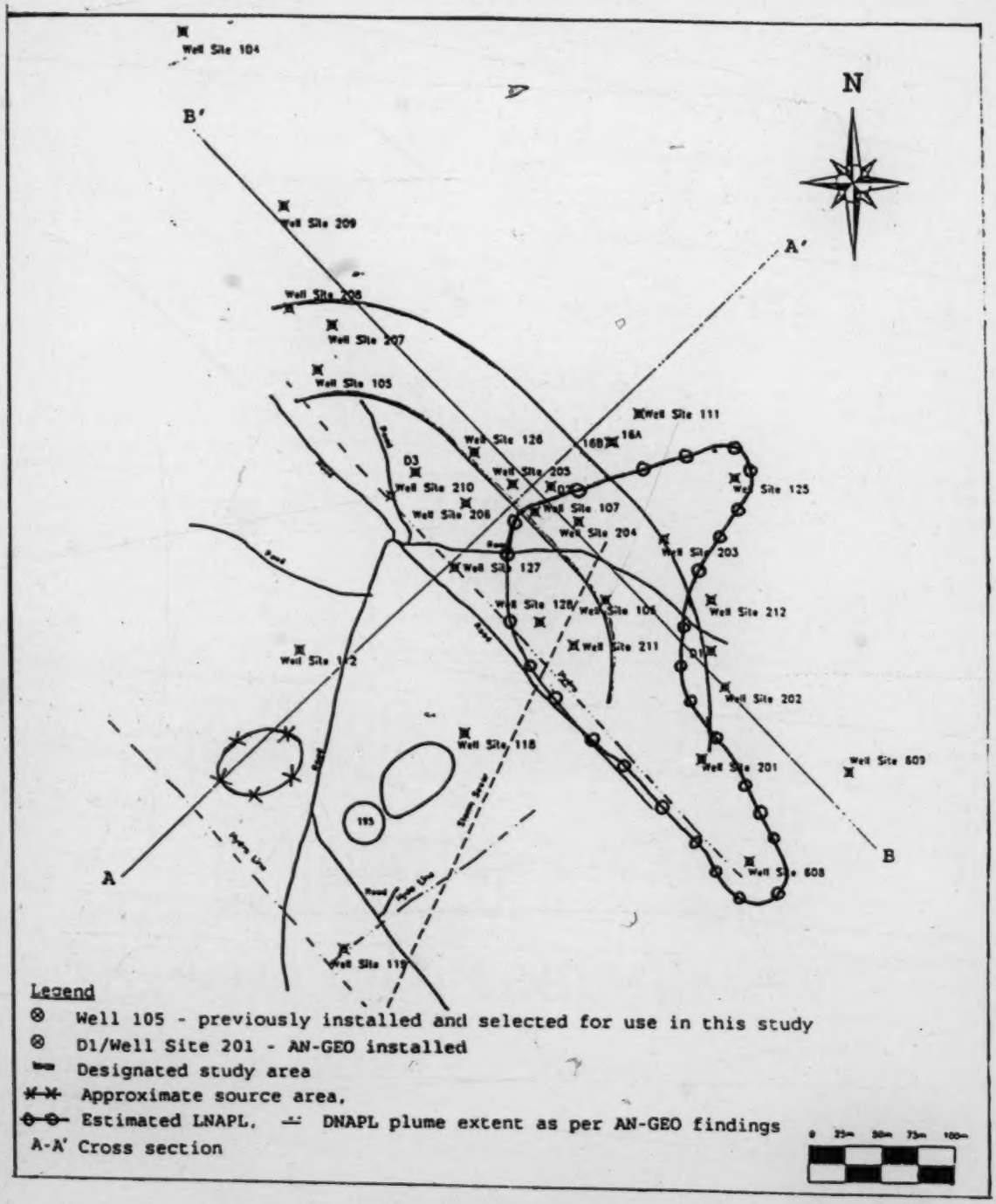


Figure 11: Site Plan from An-Geo Investigation, (Source: AN-Geo, 1997)

Since it was recommended that a funnel and gate system would not be feasible, An-Geo recommended that the contaminant source be removed and that the wells where LNAPL was found be used to recover the free-product floating on the watertable. It was also suggested that an interception trench in the bog could supplement this remedial action. In addition, assessment wells should be installed to locate the dense non-aqueous phase liquid (DNAPL) plume. This DNAPL could then be removed either by excavation or pumping. Finally, it was recommended that ongoing monitoring should be conducted to evaluate the performance of the recovery process.

3.4 Potential for Intrinsic Bioremediation

After reviewing the existing landfill site literature, it was evident that the site might be a viable candidate for the use of intrinsic bioremediation for both the BTEX compounds and the CAHs. The advantages of using this remediation option over other options are as follows:

1. The use of intrinsic bioremediation will reduce the volume of contaminated soil and water wastes and therefore reduce the possibilities of cross-contamination, evidenced by the attempted multi-phase vacuum extraction system conducted by IWR (1997);
2. It is less intrusive than conventional remedial options such as pump and treat systems;
3. It eliminates the waste permanently, rather than transporting it elsewhere for further treatment, evidenced by the excavation overseen by Pedersen (1996);
4. Since other treatments have been examined and carried out (excavation and funnel and gate) intrinsic bioremediation can be used in conjunction or as a follow-up to other remedial measures; and
5. Lower overall remediation costs than those associated with active remediation.

As previously mentioned, some of contaminants of concern include 1,1,1-trichloroethane (TCA) and 1,1-dichloroethane (DCA). The evidence to date indicates that 1,1,1-TCA can only be biodegraded at a significant rate under anaerobic conditions. Its complete mineralisation has been described (Vogel and

McCarty, 1987; Galli and McCarty, 1989; de Best et al., 1997) but usually 1,1-DCA and chloroethane (CA) are found as the main transformation products of TCA (Parsons et al., 1985; Galli and McCarty, 1989; Vogel and McCarty, 1987; de Best et al., 1997).

Secondly the majority of the current literature only shows these CAHs degraded at warmer temperatures (i.e. > 15°C). It is generally accepted that with every 10°C drop in temperature, the microbial rate of activity is approximately halved, (Q_{10} rule). Recent findings (Bradley and Chapelle, 1995) demonstrated that bacteria found in petroleum hydrocarbon contaminated sediments from a 5°C environment were capable of aerobically mineralising toluene at significant rates (16.3% day^{-1}). In the same study, bacteria found in more temperate (20°C) petroleum hydrocarbon contaminated sediments had aerobic mineralisation rates of toluene of 5.1% day^{-1}. Other studies (Bosma et al., 1996; Zhuang and Pavlostathis, 1995) have demonstrated that most dechlorination processes proceed only slightly slower at 4°C than at 20°C. These results suggest that intrinsic bioremediation of petroleum hydrocarbons and chlorinated aliphatic hydrocarbons in cold groundwater systems is feasible.

Bioremediation can be considered a viable remediation technique for TCA contaminated sites if complete dechlorination can be achieved. Sequential anaerobic/aerobic transformation of TCA appears to be a feasible option since both DCA and CA, daughter products of anaerobic TCA transformation, can be degraded under aerobic conditions (Oldenhuis et al., 1989; Scholtz et al., 1987). Secondly both DCA and chloroethane (CA) have been detected at the landfill site. The observation of daughter products is compelling evidence that intrinsic bioremediation is on-going despite the colder in-situ temperatures.

3.5 Proposed Methodology

Generally, a contaminated site investigation involves study of the site stratigraphy, concentration of contaminants in the soil and groundwater (both vertically and laterally across the site), and tests to assess the potential for the contaminants to migrate off-site, including velocity and direction of groundwater

movement across the site. As mentioned in Section 2.5, intrinsic bioremediation assessment requires additional information. It includes analysis of microbial populations, and determining concentrations of terminal electron acceptors (TEAs), contaminants and daughter products along groundwater flow paths. To propose intrinsic bioremediation as a solution for a contaminated site, it is also necessary to show that the plume is not expected to migrate beyond a certain point, or *point of compliance*.

Since the site stratigraphy was reasonably well documented, this study focused more on groundwater and soil sampling to determine both the lateral and vertical extent of contamination, as well as concentrations for TEAs. The study also included predictions of the likely fate and behaviour of the contaminant with respect to biological activity.

In order to collect the evidence for natural attenuation at cold temperatures, and to complete the previously defined objectives of the study, the research was divided into four separate phases.

PHASE I: Site Investigation

Involved the following activities:

- Properly delineating the dissolved chlorinated hydrocarbon plume and the associated source(s);
- Gathering accurate hydrogeological data (hydraulic gradient, hydraulic conductivity, stratigraphy, etc.) for the site; and
- Gathering accurate geochemical data, identifying whether additional monitoring wells and boreholes were required for the site.

PHASE II: Analysis of Contaminant Concentrations and TEAPs Across the Site

Involved interpretation of groundwater chemical and geochemical data from various standard laboratory analyses.

PHASE III: Microbial Laboratory Study

Involved determining whether a viable population of indigenous microorganisms was active at the in-situ temperatures (approximately 6°C) colder than those typically reported in the literature. This was accomplished by:

- Conducting Most Probable Number (MPN) studies at low and moderate temperatures.

PHASE IV: Fate and Transport Modeling

The information gathered in the above phases was used as input for a fate and transport computer screening model to predict whether intrinsic bioremediation is a feasible option at the site of interest.

4.0 FIELD SITE INVESTIGATION

An initial visit to the site was conducted from May 13 - 15, 1998. At this time the existing 1 CEU (1989), Royal Roads (1992) and An-Geo (1997) monitoring wells were inspected and water levels measured. Shortly thereafter, from June 14 - 17, 1998 a more detailed groundwater investigation was conducted. Water levels were measured and water samples were taken and subsequently sent to Enviro-Test Laboratories (ETL), Edmonton for analysis. In addition to these two visits, geological and site maps as well as aerial photographs were reviewed and interviews conducted with Base personnel. This information coupled with the analytical results of the first sampling round revealed the need for further water analysis as well as soil analysis. Figure 12 shows the location of all the wells and sampling sites.

From August 6 – 16, 1998 water levels and water samples were taken from existing monitoring wells. Auger drilling for soil samples, installation of two monitoring wells and drive point sampling (or hydropunching) for groundwater samples were also conducted. The well installation and drive point sampling are discussed in Section 4.1. The last sampling field investigation was conducted from October 1 – 9, 1998. During this sampling round, hydropunches were conducted and water levels and water samples were taken. Drilling to obtain the soil samples used in the microbial rate study was also conducted. On the last day, a video camera inspection of the storm sewer line that drains into the ditch was also attempted, but the drain was

almost completely clogged with sediment. Points of entry and exit manholes are labelled 1 through 4 on Figure 12. Finally, from November 7 – 8, 1998 a total station survey of the site was conducted to accurately locate all of the sampling locations.

Sites were sampled in sequence from least contaminated to most contaminated. A rigorous quality control and assurance program was also used during the field sampling. This included the use of field, rinsate and equipment blanks and 10% of the samples were conducted in duplicate. The results of the duplicate samples were within an acceptable margin of error (within 10% of one another). The rinsate and equipment blanks all had non-detectable amounts of contaminant, (refer to Appendix I).

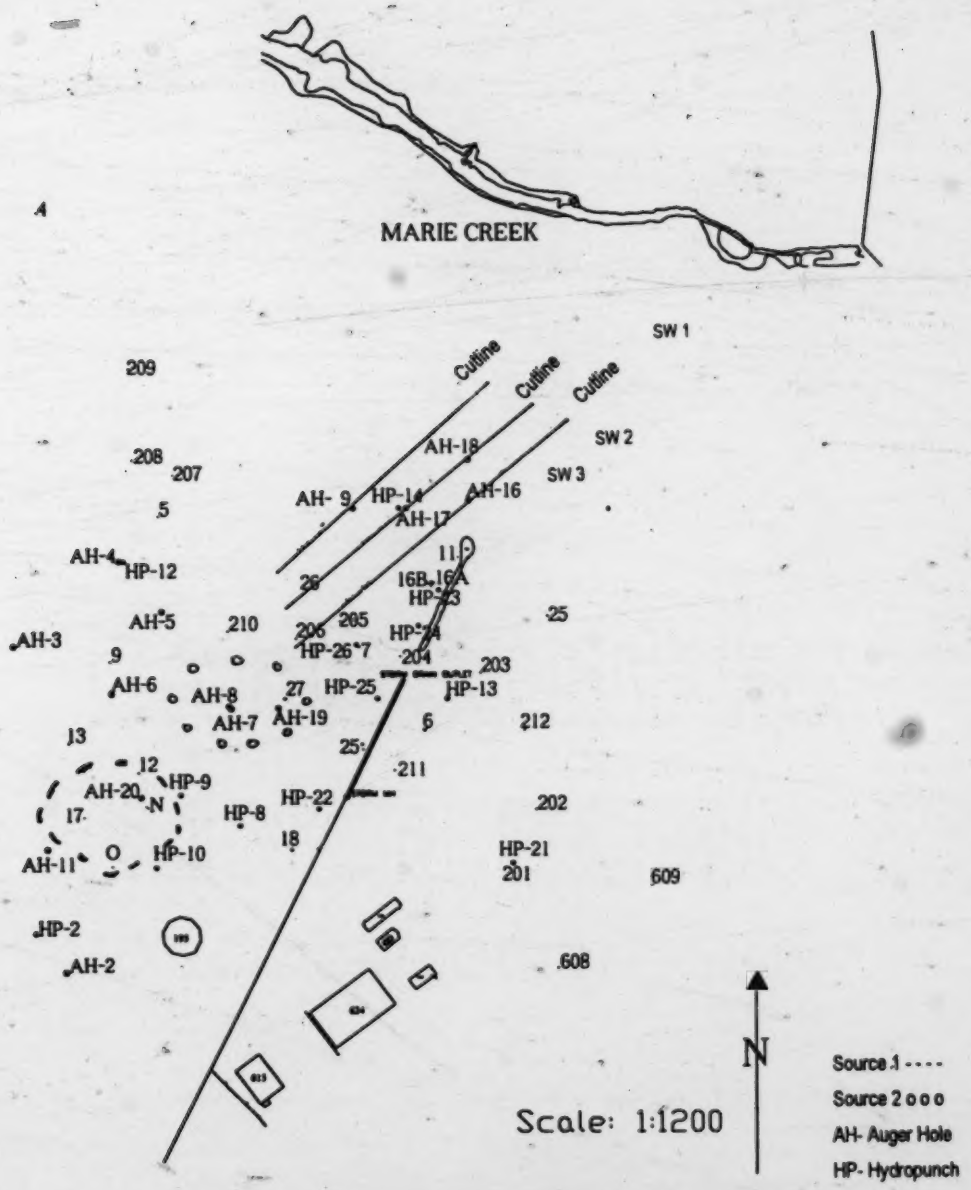


Figure 12: Sample Locations from University of Alberta Study

4.1 Groundwater Sampling

Groundwater was sampled at approximately 65 locations, which are summarised in Table 1.

Table 1 : Groundwater Sample Locations

LABEL ON Figure 12	DESCRIPTION	TOTAL NUMBER
1 - 11	Wells installed by 1 CEU, 1989	11
12 – 28,	Monitoring wells installed by Royal Roads Military College (RRMC) Environmental Sciences Group, 1991	18
201 - 212	Monitoring wells installed by An-Geo Environmental Consultants Ltd., 1997	12
AH-07 and AH-08	Monitoring wells installed by University of Alberta and Mobile Augers Edmonton, 1998	2
SW 1 – SW 3	Surface Water samples taken by University of Alberta, 1998	3
HP-5 – 15 HP-21 - 26	Drive point sampling or hydropunching conducted by University of Alberta and Mobile Augers Edmonton, 1998	17

Prior to groundwater sampling, the well would be purged of three well volumes. Most of the monitoring wells were then sampled by *micropurging*, using a Well Wizard pneumatic bladder pump. In this method, water was pumped from the formation at a relatively slow rate, (approximately 600 mL/min), and the pH, dissolved oxygen (DO), reducing-oxidizing potential (redox), temperature and electrical conductivity were monitored in a flow-through cell, (Figure 13). After these parameters had stabilised, their values were recorded, (a sample log can be found in Appendix A). At this time it was assumed that formation water was being withdrawn rather than stagnant water which may have remained in the well screen.

Figure 13: Photograph of Monitoring Well Sampling with Bladder Pump

If an insufficient amount of water existed in the monitoring well to use the bladder pump system (less than 1.5m), a disposable, hand-held bailer was used. The bailer consisted of a tube made of contaminant-free poly vinyl chloride (PVC) with a check valve at the bottom, having the following dimensions: 3.8cm outer diameter and 96.5cm length, with a volume of 1000 mL. A slow-flow valve was attached at the bottom of the bailer after it was withdrawn from the well, and the water was transferred to the appropriate sample vials. The slow-flow valve was used to minimise the loss of volatile organic compounds (VOCs) during the transfer process.

Groundwater samples were also taken for the microbial rate study at wells 27 and N. Sample N was considered to be in the source zone of contamination, while sample 27 was downgradient but still in the contaminated plume. Water samples were placed in 1L, glass mason jars with Teflon™ lined lids that had been sterilised by autoclaving at the University of Alberta. These samples were stored in the dark at 4°C until they were prepared for the microbial rate study.

The bladder pump system was decontaminated using a three-step process involving a distilled water rinse, followed by a methanol rinse and followed again with a distilled water rinse as recommended by Parker (1995).

4.1.1 Monitoring Well Installation

As previously mentioned, two monitoring wells (AH-07 and AH-08) were installed at the site during the August 1998 field visit. Previously installed wells at other CFB Cold Lake sites did not have adequate sand pack installations around the screen, allowing formation soils to migrate through the screen and into water samples. Therefore it was decided that prepacked well screens would be used for the well installations. The prepacks consisted of a 50 mm inner diameter #10 well screen with a length of 0.8 m (2.5') and a 100 mm outer diameter screen with #10 slots, with Sil #9 sand poured into the annulus between, (refer to Figure 14).

Figure 14: Photograph of Prepack Well Screen

Two wells were installed at the site (nested well configuration) to investigate the possibility of contamination in the lower aquifer. AH-07 was installed first in the upper aquifer to a depth of ~4.2m. Well AH-08 penetrates through the till aquitard and into the lower sand aquifer to a depth of approximately 11.3m, (refer to Appendix B for well configurations).

The formation sand was allowed to collapse around the prepacked well screen of AH-07 to a height of 0.6 m above the well screen, with the rest of the hole filled with bentonite chips. A 1.3m long (4'4") riser was placed below the well screen. The purpose of the riser was to ensure that during subsequent slug testing, the slug could be lowered into the riser and not inhibit the migration of water through the screen. To seal the bottom of the installation, a plug of bentonite chips was created.

During the installation of AH-08, the formation soils had a tendency to flow inside the hollow stem auger when the plug was removed to install the well screen. As a result, it was necessary to maintain a positive pressure in the well stem during the installation by keeping the hollow stem filled with water to a height of approximately 2m higher than the groundwater table. This seemed to work effectively in the sense that there appeared to be no ingress of formation sand into the drill stem that could adversely affect the well installation. Since the well screen was in the lower sand aquifer, the borehole was infilled with sand up to 3.1m above the top of the well screen, (grout would have simply squeezed into the aquifer). Above the sand, 0.6m of peltonite was placed followed by grout filled to ground surface. A riser was not placed at the bottom of this well since it was anticipated that the slug for the hydraulic conductivity tests could be placed below the water level sufficiently above the well screen so that it would not affect the water flow through the screen. All drilling equipment was steam cleaned after it was removed from the ground prior to drilling a new hole.

Two days after the wells were installed they were developed. Developing the wells involved flushing water down the wells followed by pumping with the Well Wizard pneumatic development pump to clear fines that may have migrated into the well during the installation. This process was continued until the water was sufficiently clear, (slightly turbid). All of the water removed was placed in clearly marked 200L barrels for disposal by 4 Wing personnel.

4.1.2 Drive Point Sampling (Hydropunching)

Hydropunching involves driving a small diameter hollow rod below the watertable to a depth of interest, then lifting the outer casing a predetermined amount to expose a stainless steel screen, allowing water to flow into the screen over a discrete elevation interval, (refer to Figure 15).

A Waterra™ pump connected to a Teflon™ lined tube was then used to collect the water sample. Samples were obtained at a single depth for each hole, and after each sampling the sampler and rods were removed and steam cleaned. The Waterra™ pump and tubing were also decontaminated using the previously mentioned three-step process, as recommended by Parker (1995).

All water samples were stored at 4°C in dark coolers during the day and moved to a refrigerator in the evening until they were shipped to ETL for analysis.

Figure 15: Photograph of Drive Point Sampler Used for HP Groundwater Samples

4.1.3 Groundwater Collection and Storage

All of the groundwater samples were collected by letting the groundwater sample flow down the side of the vial to prevent gas bubbles forming and/or loss of VOCs. The samples were filled to capacity, allowing no headspace. Sample vials were made either of glass or polyethylene with a screw top lid coupled with a butyl rubber, Teflon lined septum. Table 2 summarises the details of vials used as well as any preservative added for sample storage.

Table 2 : Groundwater Sample Preservation Details

ANALYTE	CONTAINER VOLUME AND TYPE	PRESERVATIVE
Routine (NO_3^-, NO_2^-, Cl^- and SO_4)	500 mL polyethylene	None added
Sulfide	100 mL polyethylene	1 mL zinc acetate 1mL of 6 normal sodium hydroxide
TOC	100 mL amber , linerless cap	1 mL 1:1 sulfuric acid
Nutrients (K, N)	500 mL polyethylene	2 mL 1:1 sulfuric acid
VOC	three, 40 mL glass vials	sodium thiosulfate
Fe^{2+}	40 mL glass vial	0.4 mL 6N hydrochloric acid
Methane	40 mL glass vial	0.1 mL 6 normal hydrochloric acid

4.1.4 Groundwater Analysis

The groundwater samples were sent to Enviro-Test Laboratories and analysed for either all or some of the following parameters:

- VOC Trace: including chlorinated hydrocarbons and BTEX. Refer to Appendix C for sample VOC trace;
- Total Organic Carbon (TOC);

- Routine water chemistry: includes bicarbonate (HCO_3^-), calcium (Ca^{2+}), carbonate (CO_3^-), conductance, hardness, hydroxide (OH^-), magnesium (Mg^+), pH, potassium (K^+), Sodium (Na^+), total dissolved solids (TDS) and total alkalinity;
- Terminal electron acceptors: includes nitrate (NO_3^-) + nitrite (NO_2^{2-}) = N and sulfate (SO_4^{2-}); and
- Metabolic by-products: iron (II), methane and chloride (Cl^-).

The test methods used by ETL for extracting and analysing the samples can be found in Appendix C.

As previously mentioned, pH, electrical conductivity, redox potential, and temperature were measured in a flow through cell by hand held meters. These meters were calibrated at the beginning of the day as well as periodically throughout the day. Dissolved oxygen was measured with the hand held meters in the flow through cell for hydropunch samples as well as downhole in the monitoring wells and checked periodically with a colourimetric Chemets™ kit. The descriptions of the hand held meters are summarised in Table 3.

Table 3 : Description of Hand Held Meters

PROBE	DESCRIPTION
Dissolved Oxygen Meter	LaMotte DO 4000
Electrical Conductivity	Oakton WD-35607-30
pH/temperature	Oakton WD-35615-Series

Samples for analysis of methane gas in groundwater were also collected. They were stored in 40 mL vials (actual volume was 43. 8 mL) with no headspace, and were analysed within 10 days of collection in Dr. P. Fedorak's Laboratory at the University of Alberta. The analysis was conducted with an HP 5700A flame ionisation gas chromatograph (GC) equipped with an uncoated Tenex™

GC, 60/80 mesh. Detailed specifications and operating conditions for the GC can be found in Appendix D.

The methane extraction was conducted similarly to the procedure outlined by Kambell and Wilson, (1989), with the exception of using nitrogen gas to create a 4 mL headspace in the sample instead of helium. After the methane was analysed, the actual concentration of methane in the water sample was calculated by the following equation:

Equation 2 : Total Concentration of Methane

$$C = \frac{M_w + M_g}{V_w} = MW\left(\frac{55.5}{H} + \frac{V_g}{V_w}\frac{1}{22.4}\frac{273}{T+273}\right)\cdot x_g$$

Where:

C	total concentration of methane in water (g/L)
M_w	mass of methane in water (g)
MW	molecular weight of methane (g/mol)
M_g	mass of methane in the gas (g)
H	Henry's Constant (dimensionless = x_g/x_w)
T	sample temperature (°C)
V_g	volume of gas or headspace (mL)
V_w	volume of water (mL)
22.4	volume that 1 mole of gas occupies at standard pressure and temperature (L)
273	standard temperature (°K)
55.5	molar concentration of water (mol/L)
x_g	mole fraction of methane in the gas

Standard curves and detailed calculations for the methane concentrations can be found in Appendix D.

4.2 Soil Sampling Program

Fourteen soil samples were taken at various depths throughout the site. Twelve samples were taken to better characterise the plume, and among those, three were taken both for characterisation and used for the

microbial Most Probable Number Study (MPN), to be discussed in Section 7.1. Since the emphasis of this study was groundwater analysis, all the soil samples were taken below the groundwater table. Table 4 summarises the depths at which each soil sample was taken. All soil samples with the exception of AH-08 were taken with the solid stem auger.

Table 4: Boreholes and Associated Depth

BOREHOLE	DEPTH OF GROUNDWATER TABLE
AH-02	2.3m (7.5')
AH-03	2.1m (7.0')
AH-04	1.7m (5.5')
AH-05	1.8m (6.0')
AH-06	2.1m (7.0')
AH-07	2.0m (6.5') 2.3m (7.5') 3.4m (11.0')
AH-08	11m (36.0')
AH-09	0.8m (2.5')
AH-16	0.8m (2.5')
AH-17	0.46m (1.5')
AH-18	no sample
AH-19	2.3m (7.5')
AH-20	2.6m (8.5')

4.2.1 Solid and Hollow Stem Augering

Soil samples were taken by either a 0.13m (5") inner diameter hollow stem auger or a 0.15m (6") outer diameter solid stem auger (refer to Figure 16).

When the solid stem auger was brought to the surface, the outer layer of the soil on the auger flights (approximately 3 cm thickness) was scraped off with a straight edge and disposed of. The remaining soil was then carefully placed in three 500mL glass jars with Teflon™ lined lids. With the hollow stem auger, a split spoon sampler was driven into the soil with an standard penetration test (SPT) hammer. A split spoon with a 8.6 cm (3 3/8") inner diameter was used. The core sample was split lengthwise with a sampling knife, logged, then placed in sample jars as appropriate. After

each borehole the augers were washed with detergent and then rinsed twice with distilled water and methanol.

In order to reduce the risk of volatilisation, Hewitt (1994) stated that 10mL syringes should be used to extract samples from the core sample then immediately eject them into 40mL sample vials. This procedure was used previously at another Cold Lake site, but it was found that representative samples could not be procured due to the small sample size and localised heterogenieties in the contamination. Therefore, as much of the soil within the specified zone was sampled and placed immediately into glass jars, sealed from the air.

As previously mentioned, three of the soil samples were taken for a microbial MPN study. These samples were upgradient (AH-01), in the middle of the zone of contamination (AH-07) and as far downgradient from the source as possible (AH-17). These soil samples were filled to capacity (i.e. no headspace) in 1L screw cap, polyethylene bottles that had been sterilised at the University of Alberta by autoclaving.

Aseptic methods were used during all soil sampling. Distilled water followed by methanol and a final rinse with distilled water was used to clean all sampling tools (spatula, straight edge, knives, etc.) between boreholes. Samples were stored in the dark at 4°C until they were prepared for laboratory use.

Figure 16: Photograph of Solid Stem Auger and Soil Core from SPT Sampling

4.2.2 Soil Vapours

Two different types of soil vapour measuring meters were used to measure carbon dioxide, oxygen (O_2) and the Lower Explosive Limit (LEL). Soil was placed in a Ziplock™ type plastic bag, and the sample was left for approximately 30 min, to allow the vapours to come to equilibrium. The sampling tube from the meter was then inserted in the bag, and a reading was taken. Shortly after sampling began, it was evident that neither the LEL nor the O_2 meters were working correctly. Therefore, no meaningful results could be obtained. CO_2 measurements however were recorded.

4.3 Hydrogeological Investigation

4.3.1 Site Survey and Groundwater Table Elevations

Groundwater elevations were measured at approximately 60 locations to determine the gradient across the site as well as the direction of groundwater flow. This was conducted on 5 occasions between May and November, 1998. In November, a total station survey was conducted to determine the locations of the wells with respect to one another as well as to establish their ground elevations.

4.3.2 Permeability Tests

Field slug tests were performed to determine the permeability of the upper sand aquifer. A total of 9 tests was completed at three different monitoring wells. The slug test involved submerging a pressure transducer close to the bottom of the well. The slug (60cm in length and 42mm in diameter, made of PVC) was then rapidly lowered slightly above the pressure transducer. The change in pressure due to the rise in the water level in the well was recorded every second using a data logger. This change was then translated into a water level (refer to Appendix E). Data were also recorded when the slug was removed from the well. This procedure was repeated at least four times for each well to ensure repeatability, as recommended by Butler et al. (1996).

The results were analysed using the software package AQTESOLVE™. AQTESOLVE™ features a suite of analytical solutions for determining aquifer properties. It was decided that the Bouwer-Rice (Fetter, 1992) solution for unconfined aquifers would be employed. Further details are discussed in Section 5.3.

5.0 HYDROGEOLOGICAL ANALYSIS

5.1 Soil Stratigraphy

The stratigraphy at the site has been reasonably well defined by previous studies. Much of the information described below was taken from the 1 CEU report (1989), the RRMC report (1991) and the An-Geo report (1997) all of which undertook a comprehensive subsurface investigation. In addition to the 48 boreholes from these three studies, 13 more were drilled by the U of A. All of the borehole logs can be found in Appendix B. Cross sections of the site from the An-Geo report are shown in Figures 19 and 20. Figure 19 shows the location of the wells used for the above cross-sections.

The local geology consists of four strata: a shallow organic layer, a silty sand layer, till and finally sand again. The first layer is 0.1 to 0.6m of organic matter including vegetation and wood pieces found at the surface. A poorly graded, silty sand (classified as SM in the Unified Soil Classification System - USCS) layer exists below the organic matter. It was orange to olive brown and water bearing. The grain size changes from fine/medium to coarse as the density decreases from compact to loose with increasing depth (An-Geo, 1997). On average the silty sand surface layer overlying the clay barrier is 2.5m thick. It is 3 to 3.5m in the region bounded by wells 15, 22, 28 and 27; decreases to 2 to 2.5m along the line joining wells 5, 7 and 26 and drops to 1.5m at well 16; and is absent at well 25 and beyond (RRMC, 1991).

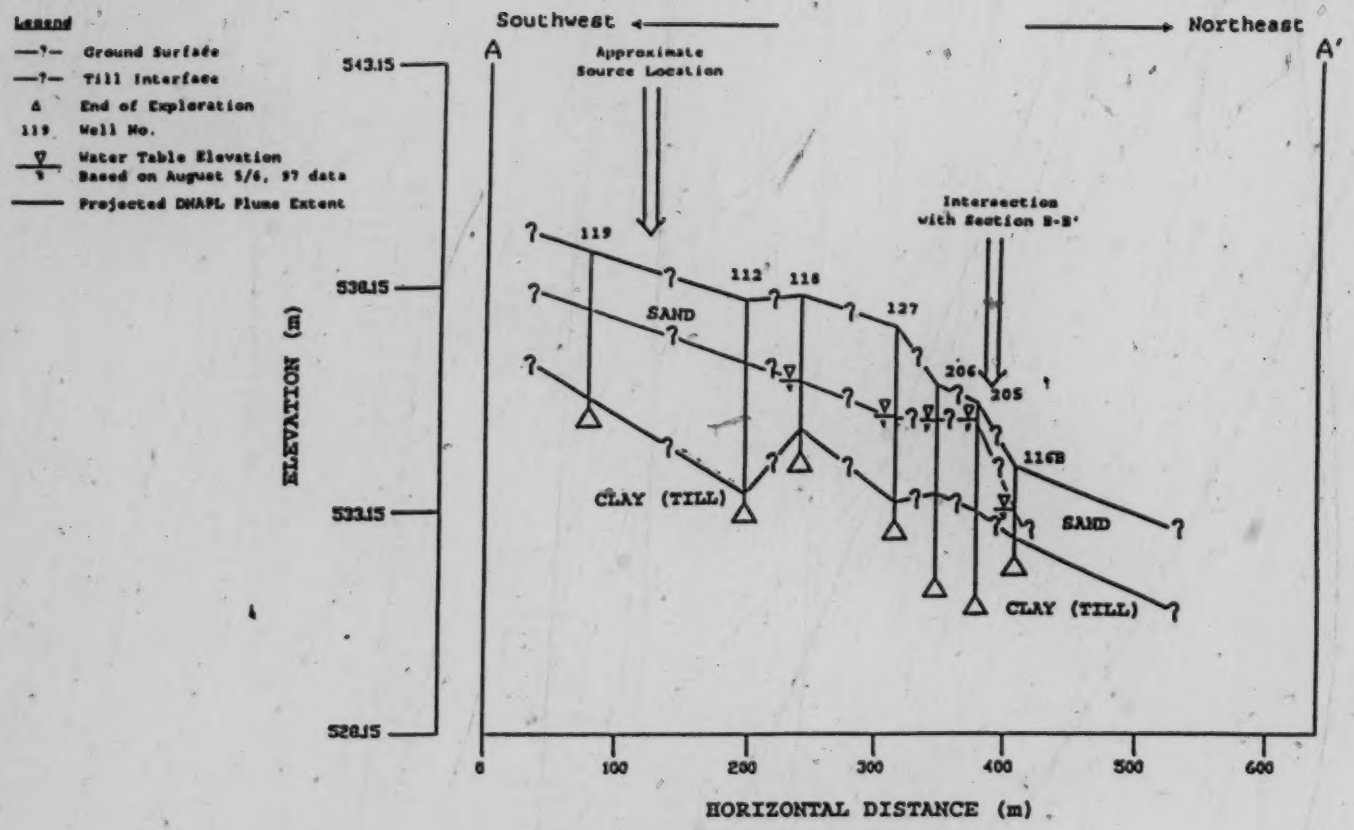


Figure 17: Geological Cross-Section A-A' (Source: An-Geo Report, 1997).

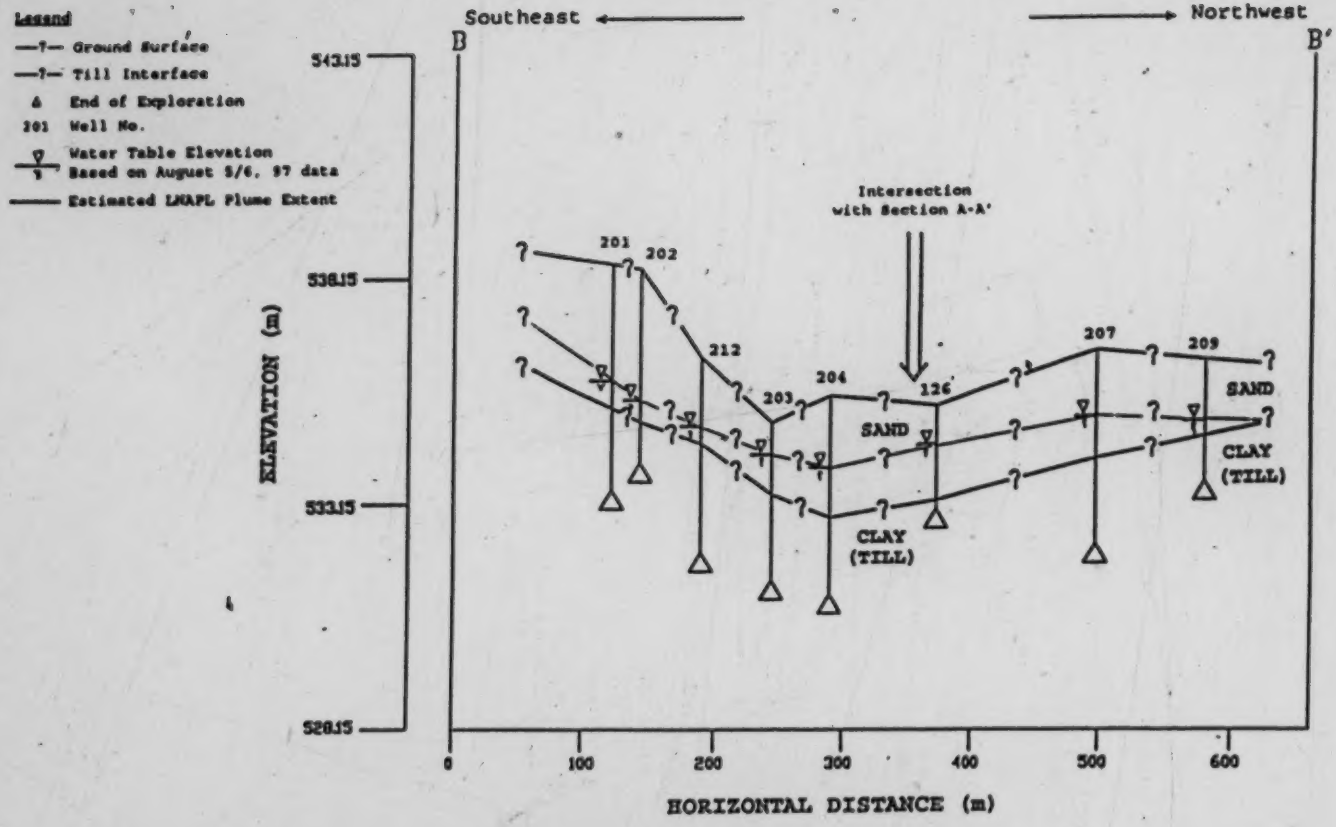


Figure 18: Geologic Cross-Section B-B' (Source: An-Geo Report, 1997).

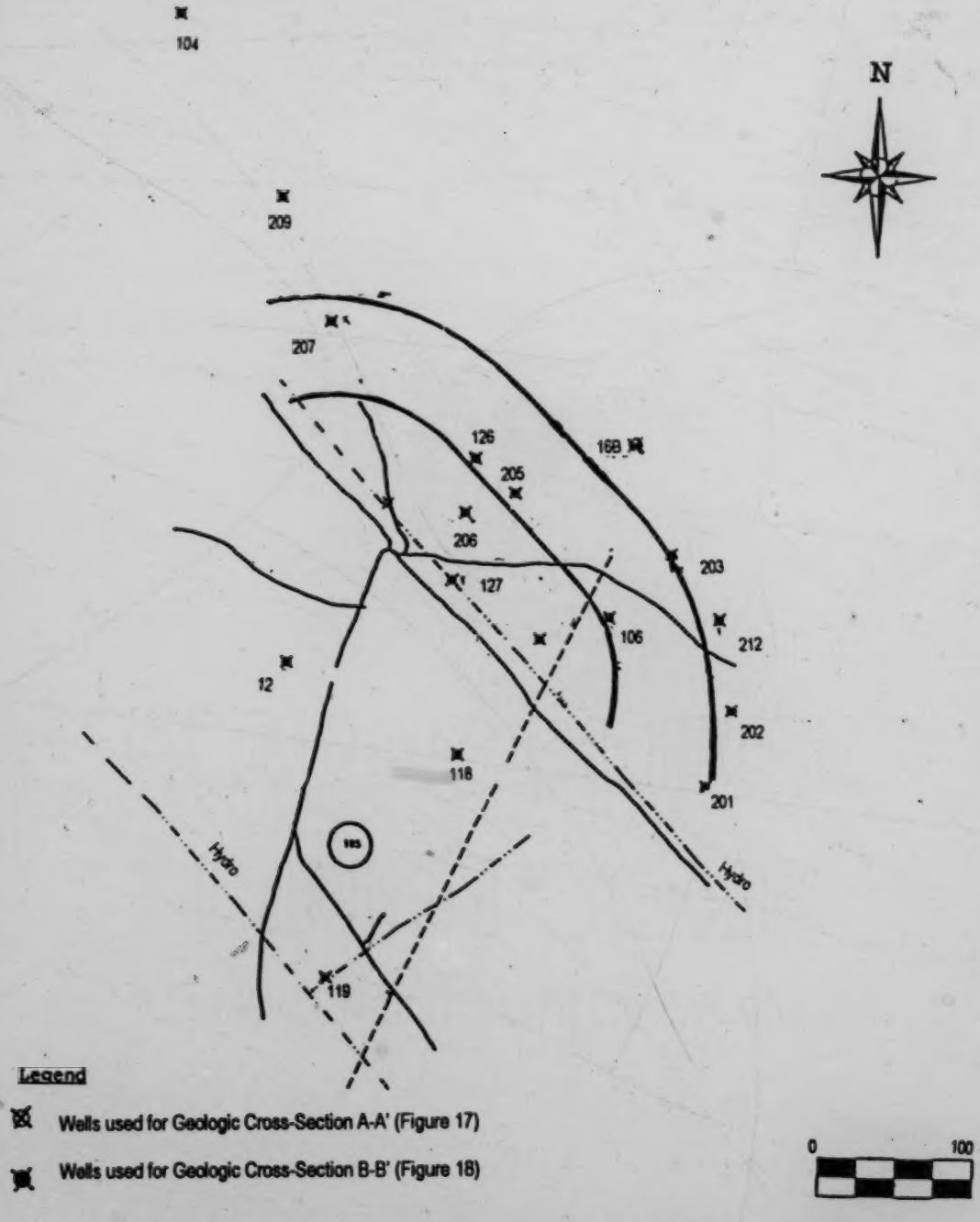


Figure 19 : Plan View of Geologic Cross-Sections (Adapted from An-Geo, 1997)

The clay till is silty and sometimes sandy (CL according to the USCS), dark grey to black with occasional sub-rounded gravel. It is uniform with little moisture. The consistency of the till increased significantly from firm to very stiff within 1m of depth. Although there was no recovery at a depth of 9.9 to 10.7m (32.5 to 35.0 ft), in AH-8, it was assumed that the second silty sand layer began at 9.9m since sand was encountered at 10.7m (35.0 ft). The second silty sand layer was similar to the first silty sand layer, but with a lower moisture content.

A sieve analysis was also conducted at the University of Alberta from the upper sand at AH-19, near well 27. The sand was classified using the Unified Classification system as poorly graded, silty sand (SM) with approximately 5% passing the No. 200 sieve. The coefficient of uniformity (C_u) for the sand was 4.0. Details of the sieve analysis can be found in Appendix F.

5.2 Groundwater Table Elevations: Hydraulic Gradient Across the Site

The watertable of the site is located in the upper sand layer at a depth of approximately 2.5m and is under unconfined conditions. This was determined by taking water level readings in the existing monitoring wells, hydropunches and the two wells installed by the University of Alberta. Monitoring groundwater elevations took place over a five month period between May and October 1998. The measured groundwater elevations for June August and October and corresponding site survey are summarised in Appendix G. Interpretative isopleth maps of the groundwater elevations are shown for June, August and October in Figures 22 to 24. The watertable in the lower sand aquifer was at approximately 11m, which is below the base of the clay aquitard, and therefore was also unconfined.

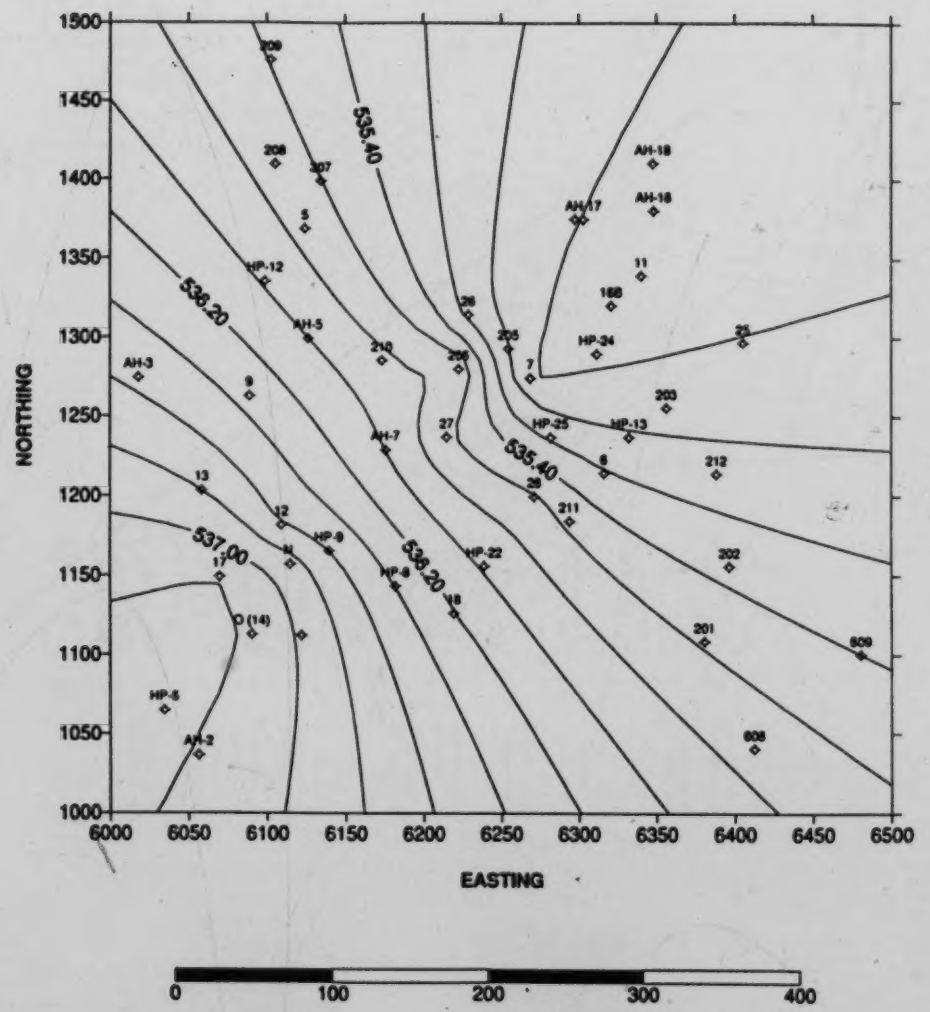


Figure 20: Groundwater Elevations - June 1998

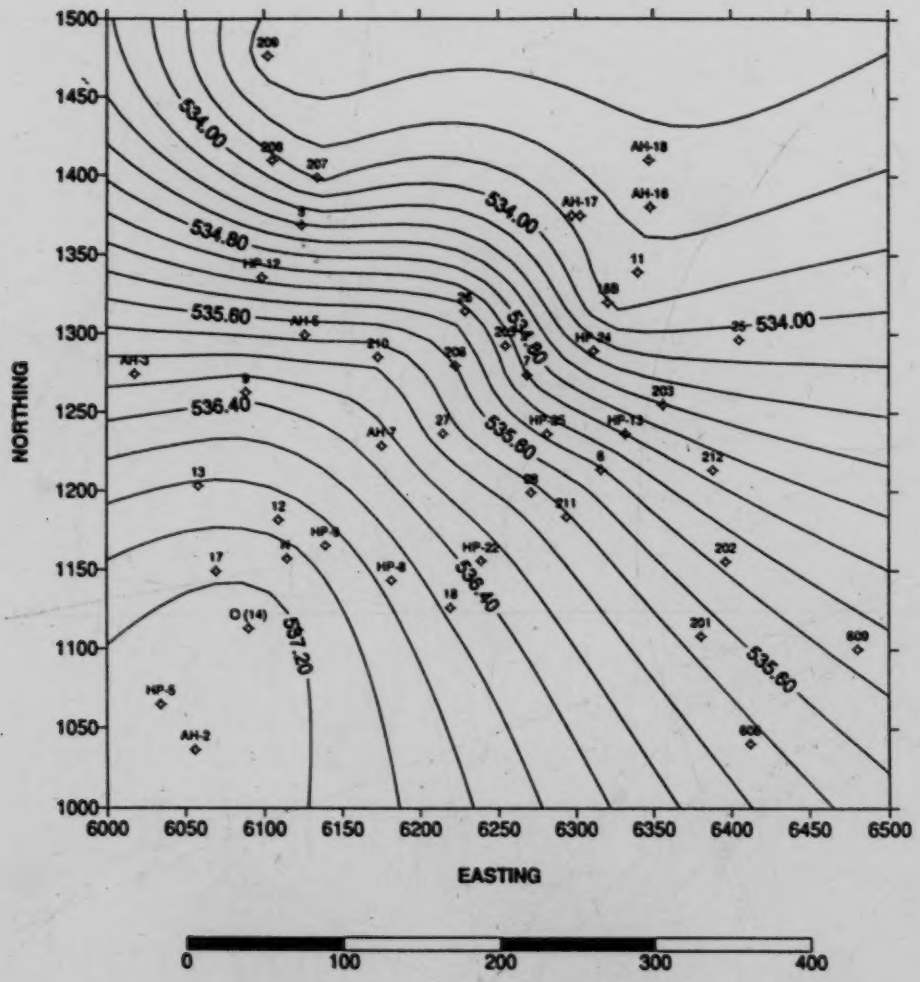


Figure 21: Groundwater Elevations - August 1998

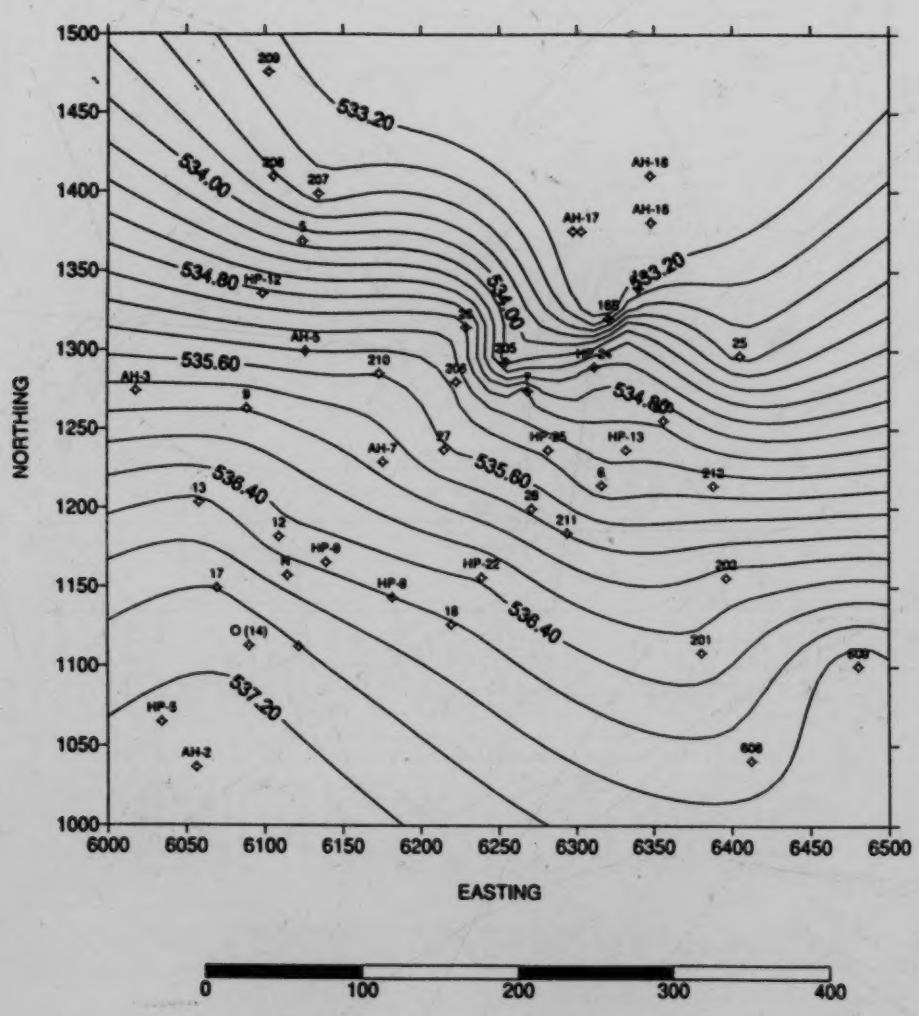


Figure 22: Groundwater Elevations - October 1998

Two key points can be inferred from the above figures. First, flow direction remained relatively constant over the monitoring period with groundwater flowing in the north-easterly direction. Both RRMC and An-Geo also observed this direction of flow. Secondly, the hydraulic gradient (i) across the site ranged from 9.23×10^{-3} to 0.13×10^{-3}, with an average of 0.11×10^{-3}. The hydraulic gradient of a site is the slope of the potentiometric surface, or in unconfined conditions is equivalent to the slope of the watertable.

The maximum gradient across the site varied between sampling periods. During the month of June it was approximately 9.2×10^{-3} (between monitoring wells 17 and 7), whereas in August the maximum gradient was approximately 0.11×10^{-3} (between monitoring wells 17 and 16B). Finally, in October the maximum gradient was approximately 0.13×10^{-3} (between monitoring wells17 and AH-17). It should be noted however, that a water level was not taken for well 11 in either June or October's sampling event.

5.3 Hydraulic Conductivity

The hydraulic conductivity (K) of the upper sand layer was determined in 1998 by conducting in-situ slug tests on wells 204 and 206 (An-Geo) and AH-7 (University of Alberta). As described in Section 4.3.2, a solid, PVC slug with a volume of 8.31×10^{-4} m^3 was used to initially displace 72.4 cm of water in each well. The change in water level was recorded every second using a data logger connected to a pressure transducer at the bottom of the well. After the water level had stabilised, the slug was rapidly removed and the changes in water level were again recorded. This process was repeated 3 or 4 times for each well. The data obtained from the slug tests were then input into the software package, AQTESOLV™.

AQTESOLV™ has a suite of analytical solutions for determining aquifer properties. After reviewing the solutions available, the Bouwer-Rice (1976) solution for slug tests in an unconfined aquifer was chosen to estimate the hydraulic conductivity. The Bouwer-Rice solution is based on the following equation, (refer to Figure 23).

Equation 3 : Bouwer-Rice Solution for Unconfined Aquifers (after Bouwer, 1989)

$$K = \frac{r_c^2 \ln(R_e / R)}{2 L_e} \frac{1}{t} \ln \frac{H_t}{H_0}$$

Where:

K	Hydraulic conductivity (L/T)
r_c	radius of the well casing (L)
R	radius of the gravel pack (L)
R_e	effective radial distance over which head is dissipated (L)
L_e	length of the screen or open section of the well through which water can enter (L)
H_0	Drawdown at time $t = 0$ (L)
H_t	Drawdown at time $t = t$ (L)
t	Time since $H = H_0$ (T)

The following parameters were used in the model: porosity, initial displacement, height of water column, depth of saturated aquifer, length of screen, casing and well radius and anisotropy ratio.

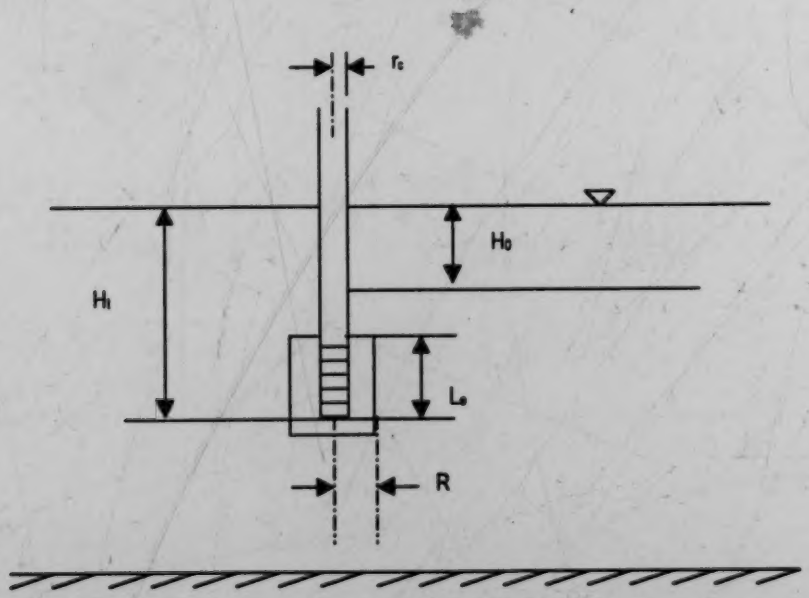


Figure 23 : Geometry and Symbols for Bouwer-Rice Solution for Unconfined Aquifers

A sensitivity analysis was conducted to determine how the parameters required for the Bouwer-Rice solution affected the results. Three values for the well bore radius (R) were examined: 4, 11 and 12cm. It was established that R had the most effect on the hydraulic conductivity. The variation from 4 to 12cm resulted in nearly one order of magnitude change in the hydraulic conductivity. It was however, determined that a well bore radius of 11cm was more representative of the well installations at the site, since all well installations used a hollow stem auger with a 22.9cm (9") outer diameter (11cm radius). It was also determined that the well casing radius and the initial height of the water column did not have a significant effect on the hydraulic conductivity, and therefore were maintained constant. A casing radius of 8cm was chosen since the prepacked well screens used, had an outer diameter of 15.2cm (6") or 8cm radius.

The hydraulic conductivity was also calculated by varying the anisotropy ratio (K_z/K_r) from 1 to 1/3. Results of the sensitivity analysis can be found in Appendix H. Table 5 summarises the results of the analysis keeping the casing and well bore radii at 8 and 11cm respectively.

Table 5 : Summary of Hydraulic Conductivity Results for Upper Sand Aquifer

Hydraulic Conductivity (m/s)		
WELL	$K_z/K_r = 1$	$K_z/K_r = 0.3$
204a	4.8E-05	4.8E-05
204b	6.5E-05	6.5E-05
204c	5.0E-05	5.0E-05
204aa	4.4E-05	5.3E-05
206a	9.3E-05	9.3E-05
206b	6.5E-05	6.5E-05
206c	7.2E-05	7.2E-05
206d	6.1E-05	6.1E-05
206e	8.9E-05	8.9E-05
206f	6.2E-05	6.2E-05
AH7a	7.2E-05	9.0E-05
AH7b	1.2E-04	1.6E-04
AH7c	3.9E-05	4.9E-05
AH7d	1.2E-04	1.5E-04
AH7e	6.3E-05	7.9E-05
Average	7.1E-05	7.9E-05

The average hydraulic conductivities for an anisotropy ratio of 1 and 1/3 were 7.1×10^{-5} and 7.9×10^{-5} m/s, respectively. Based on the similar results of varying the anisotropy ratio, an average of the two hydraulic conductivities was chosen (7.5×10^{-5} m/s).

The above hydraulic conductivity results were also analysed by conducting three constant head permeameter tests at the University of Alberta, (refer to Appendix H). Results indicated that the upper sand aquifer had a hydraulic conductivity ranging from 19.2×10^{-5} m/s to 20.1×10^{-5} m/s. The slightly higher (approximately three times greater) laboratory hydraulic conductivities can be attributed to either preferential flow paths that may have developed in the permeameter, or that in-situ conditions are more dense than laboratory conditions. The latter is a more likely explanation. Although higher hydraulic conductivities were found in the lab, it was believed that the more likely value in the field was 7.5×10^{-5} m/s.

5.4 Groundwater Velocities

Given the gradient (change in groundwater table elevation) across the site determined from the groundwater elevation contours, coupled with the hydraulic conductivity calculated in the field, the horizontal specific discharge may be calculated using Darcy's Law:

Equation 4 : Darcy's Law

$$v = Ki$$

Where:

v: horizontal specific discharge (m/s)
K: hydraulic conductivity (m/s)
i: gradient

Based on Equation 4, the average horizontal specific discharge in the sand layer is 7.8×10^{-7} m/s (~ 26 m/year). The average seepage velocity can be calculated by dividing the specific discharge by the effective

porosity (~ 0.34). The maximum and minimum expected permeabilities were based on the range of values used for the casing and well bore radius during the sensitivity analysis. A casing radius of 4cm and a well bore radius of 12cm, resulted in a maximum permeability. A casing radius of 2cm and a well bore radius of 4cm resulted in a minimum permeability. Maximum, minimum and expected specific discharge and seepage velocities are summarised in Table 6.

Table 6 : Expected Range of Specific Discharge and Seepage Velocities

	PERMEABILITY (m/s)	GRADIENT	SPECIFIC DISCHARGE (m/yr)	SEEPAGE VELOCITY (m/yr)
Maximum	9.9×10^{-5}	0.13×10^{-3}	40.5	119
Minimum	1.9×10^{-5}	9.2×10^{-3}	5.5	16.2
Expected	7.5×10^{-5}	0.11×10^{-3}	26	76

6.0 RESULTS OF CHEMICAL ANALYSIS

6.1 pH, Temperature, Redox Potential and Electrical Conductivity

Groundwater pH, electrical conductivity, redox potential and temperature were all measured with a flow through cell, (Figure 13) when the sample was taken with the bladder pump. All measurement results are summarised in Appendix I.

As stated by Lee et al. (1998), the pH will have an effect on the presence and activity of microbial populations in groundwater. This is especially true for methanogens (Wiedemeier et al., 1998). The optimal pH for microbes capable of degrading chlorinated and petroleum hydrocarbon compounds is in the range of 6 to 8 standard units (Lee et al., 1998). During the August sampling trip, pH values ranged from 5.7 to 8.0, with an average pH of 6.7. This pH is therefore, within the optimal range for degrading the CAHs. Similar values were obtained during the October sampling visit, where the average pH was 7.3 standard units.

It is known that groundwater temperature will directly affect the solubility of dissolved gases and other geochemical species (Blowes, 1997). Groundwater temperature will also affect the metabolic activity of microorganisms (Chapelle, 1993). During the August sampling trip, it was concluded that the temperature probe was either insufficiently calibrated or simply not functioning properly since temperature readings were much higher than expected (maximum of 14°C). Therefore, another probe was assembled for the October field visit. The results from October's sampling round indicate that the average temperature for the site is approximately 8°C in the upper sand aquifer (~2.5m depth).

The redox potential of groundwater is a measure of electron activity and is an indicator of the relative tendency of a solution to accept or transfer electrons (Wiedemeier et al., 1998). Redox reactions in groundwater containing organic compounds are usually biologically mediated. Therefore one can conclude that the redox potential of groundwater depends upon and influences rates of biodegradation (Lendvay et al., 1998). From Figure 2, it can be seen that if a redox potential less than –50 mV exists at the site, reductive pathways are likely. Although Wiedemeier et al. (1998) suggest that the value is closer to –100 mV is an indication of reduced areas, and yet others suggest that a redox potential less than zero is indication of reduced areas (Lendvay et al., 1998). Redox potentials averaged –39 mV with a high of –19 mV and a low of –70mV at monitoring well 207. These readings were taken over the entire range of monitoring wells at the site. Qualitatively, negative redox potentials indicate reductive conditions, which are associated with biodegradation processes (Chapelle et al., 1996). Therefore, the observed values indicate that in the least, that the groundwater is a reducing environment.

Electrical conductivity is a measure of the ability of a solution to conduct electricity. The conductivity of groundwater is directly proportional to the concentration of ions in solution. Electrical conductivities can be used to confirm whether all the groundwater being analysed is coming from the same source (Wiedemeier et al., 1998; Lendvay, et al., 1998). The electrical conductivity for the site was on average 1,489 µS with a

maximum of 9,100 µS at AH-07, and a minimum conductivity of 98µS at well 608. The build up of chloride in the groundwater is often used as an indicator for reductive dechlorination. Chloride at this site however, could not be used as an indicator of reductive dechlorination since high groundwater concentrations already existed as a result of a nearby salt storage building. This would explain the very high conductivities seen at the site.

6.2 Terminal Electron Acceptor (Geochemical) Analysis

To determine if microbial activity and reductive dechlorination are ongoing in the groundwater, an analysis of the depletion of the TEAs and the generation of microbial by-products of organic compound degradation was conducted. The TEAs that were examined included oxygen (O_2), nitrate (NO_3^-), which is first reduced to nitrite (NO_2^-) and finally to nitrogen gas (N_2), and sulfate (SO_4^{2-}). As shown in Figure 2, TEAs are generally used in decreasing order of the energy that they provide to microbes. The hierarchy is typically:

$$O_2 > NO_3^- > Fe^{3+} > SO_4^{2-} > CO_2$$

The by-products include iron (II) (Fe^{2+}), chloride (Cl^-), sulfide (S^{2-}) and methane (CH_4). The reduction of insoluble ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}), which is soluble, will lead to increased iron ions in the groundwater if iron-reducing bacteria (FeRB) are active. Chloride is released in the groundwater during biodegradation of chlorinated hydrocarbons dissolved in groundwater. Therefore, its presence in concentrations higher than background levels is an indication that reductive dechlorination is occurring. If sulfate-reducing bacteria (SRB) are present at the site, the sulfate in the groundwater will be reduced to sulfide. Finally, during methanogenesis (anaerobic activity), where CO_2 is used as the TEA, methane will be released as a by-product.

The results of the analysis are contained in Appendix I and the data have been plotted in Figures 24 and 25.

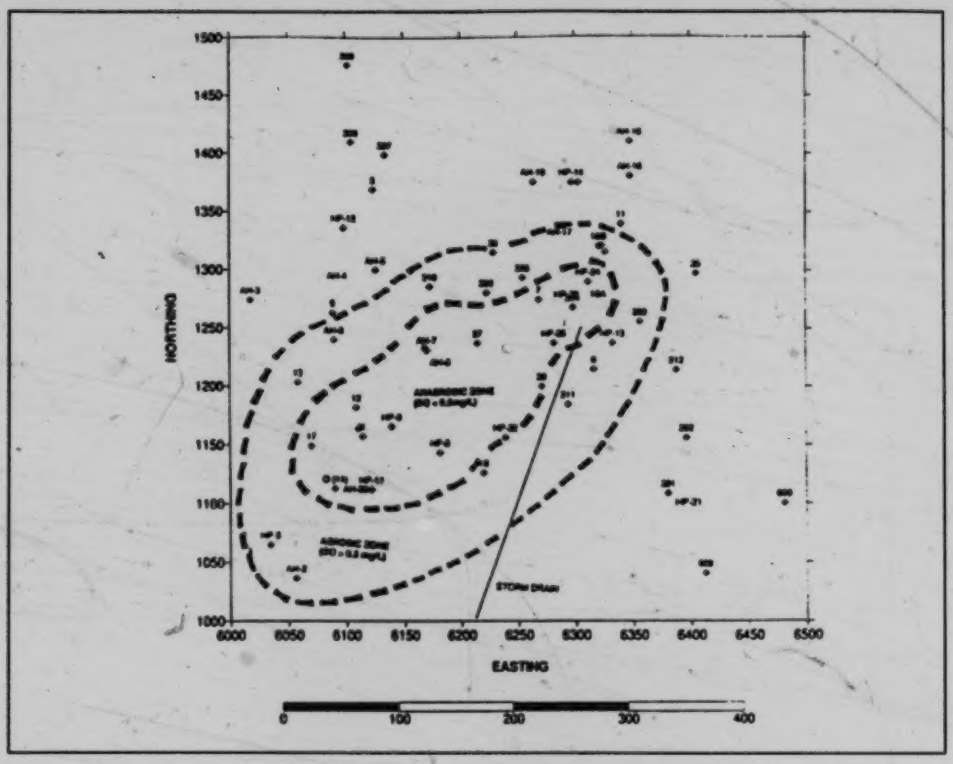


Figure 24: Interpretative Zones of Electron Acceptor Utilisation

Figure 24 shows a distinct aerobic zone along the fringe of site (background and downgradient), with DO values ranging from 6.6 mg/L at HP-5 (considered background) to 8.8 mg/L at HP-21. Towards the middle of the plume, DO values approach 0.5 mg/L at monitoring wells 12 and 28. These results correspond to the methane concentrations found in the same areas (Figure 25).

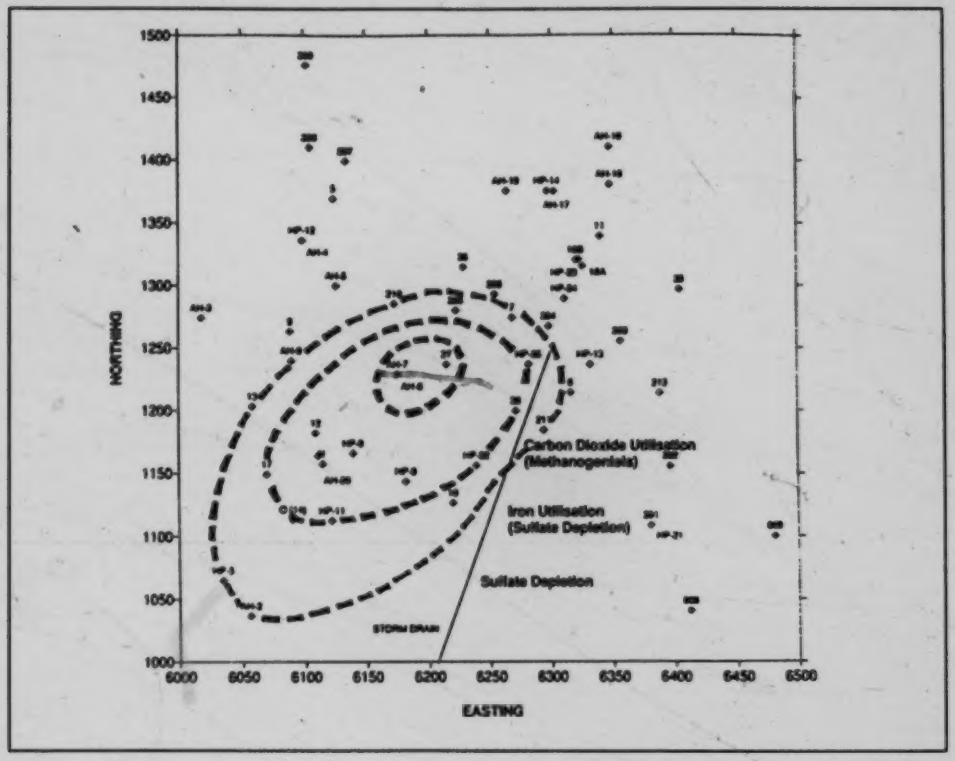


Figure 25: Interpretative Zones of Electron Acceptor Utilisation

Background concentrations of methane are non-detectable (ND), whereas towards the middle of the plume methane levels are as high as 1.0 mg/L at well 27. Wiedemeier et al., (1998) suggest that methane concentrations in excess of 0.5 mg/L indicate in-situ conditions suitable for reductive dechlorination. However, the generation of methane may also be indication of BTEX degradation. Therefore the concentrations of methane observed may indicate that either BTEX and/or reductive dechlorination is occurring. Neither nitrate nor nitrite appear in any significant quantity (max. concentration of 0.002 mg/L). This trend is discussed in Section 7.0.

In the area near wells 27, AH-07, 17 and HP-22, HP-25 and HP-08, (in the delineated anaerobic zone) there are elevated concentrations of ferrous iron, indicating that an iron-reducing zone clearly exists. Along the perimeter of this iron-reducing zone is a sulfate reducing zone (HP-11, HP-09 and wells 206 and 13). The higher sulfate concentrations agree with the lower Fe^{2+} concentrations in this delineated area. These results may indicate that BTEX degradation and reductive dechlorination are occurring and the progressive depletion of terminal electron acceptors is as expected.

6.3 Contaminant Assessment

The contaminants of concern at the study site included: BTEX, 1,1,1-TCA, 1,1-DCA and dichlorobenzenes. Analyses were performed by ETL on the groundwater at all sampling points from this study (drive point sampling and installed monitoring wells), several of the previously installed monitoring wells, and the soil from auger holes 7,8, 19 and 20. The results of these analyses are found in Appendix I.

6.3.1 Soil Analysis

During the August sampling period only AH-07 showed appreciable amounts of both CAH and BTEX contamination in the soil. AH-16 also showed contamination, but only BTEX. All other soil samples had non-detectable amounts of contamination. Based on these results, it appears that the lower sand aquifer is uncontaminated, and that the contamination is isolated in the upper sand layer. Therefore, it can be assumed that the clay till is acting as an effective barrier for vertical contamination.

In August, the groundwater elevation at AH-07 could not be determined. However, examining the groundwater elevations of nearby wells temporally, one can approximate the groundwater table was at 536.2m. At AH-07 soil samples were taken at three intervals, 536.72, 536.41 and 535.35m, the last sample being below the groundwater table. From the table shown in Appendix I, it can be seen that the greatest CAH contamination is at an elevation of 536.72m with TCA and DCB at

1000 and 4000 mg/kg (ppm), respectively. As the sampling depth increased, the CAH contamination decreased and the BTEX contamination increased.

AH-16, which is situated on one of the cut-lines north-west of well 16 showed no CAH contamination. Total BTEX concentration at this location was 240 µg/L (ppb). It does not seem likely that this contamination stemmed from the source (near wells 17 and 12), since it is not found in the direction of groundwater flow. Hence, these results either indicate a different source or are in error. This matter should be re-investigated.

6.3.2 Water Analysis

Results of the groundwater analysis are also summarised in Appendix I. Interpretative isopleth maps of BTEX, TCA and DCA can be found in Figures 26 through 28. The interpretative isopleth plots were generated using the gridding option of the software program Surfer™. Surfer™ is a contouring and 3D surface mapping and plotting program that runs under Microsoft Windows. Contour maps and surface plots can be generated using the gridding method from x, y and z data. The data can be randomly dispersed over the map area, and Surfer's gridding will interpolate the data onto a grid. There are nine gridding options to choose from. The Kriging method was chosen for the contour plots seen in Figures 26 through 28.

Kriging provides a means of interpolating values for points not physically sampled using knowledge about the underlying spatial relationships in a data set to do so. Semivariograms provide this knowledge. Kriging is based on regionalized variable theory and is superior to other means of interpolation because it provides an optimal interpolation estimate for a given co-ordinate location, as well as a variance estimate for the interpolation value.

Generally, significant concentrations of BTEX were detected in the groundwater along the length of the delineated plume, (Figure 26). Higher concentrations exist near the source (wells 17 and 12) which tend to decrease in the north-easterly direction to HP-08 and HP-09. At this point, concentrations start to increase again, peaking at 18mg/L near AH-07 and well 27. Finally, further downgradient towards HP-24 and wells 16 and 11, and along the fringe of the plume (AH-05 and HP-22) the BTEX concentrations drop to 0mg/L.

In Figure 27, it can be seen that large concentrations of TCA are found within the source (3000μg/L), and start to decrease towards wells HP-08 and HP-09. Again, as seen with the BTEX isopleths, these concentrations increase in the direction of well 27. Along the fringe of the plume and further downgradient towards wells 16 and 11, the concentrations of TCA steadily decrease to 0μg/L.

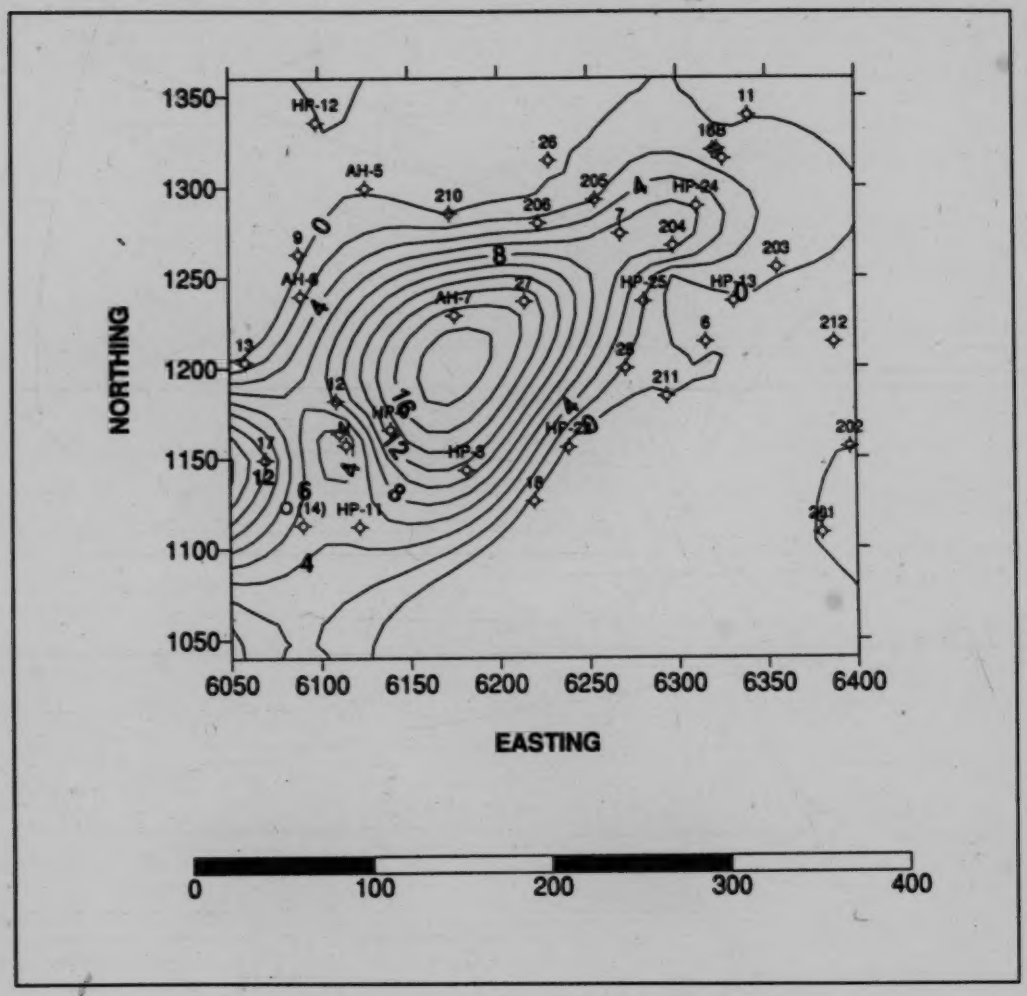


Figure 26: Interpretive Groundwater Isopleth of BTEX (ppm)

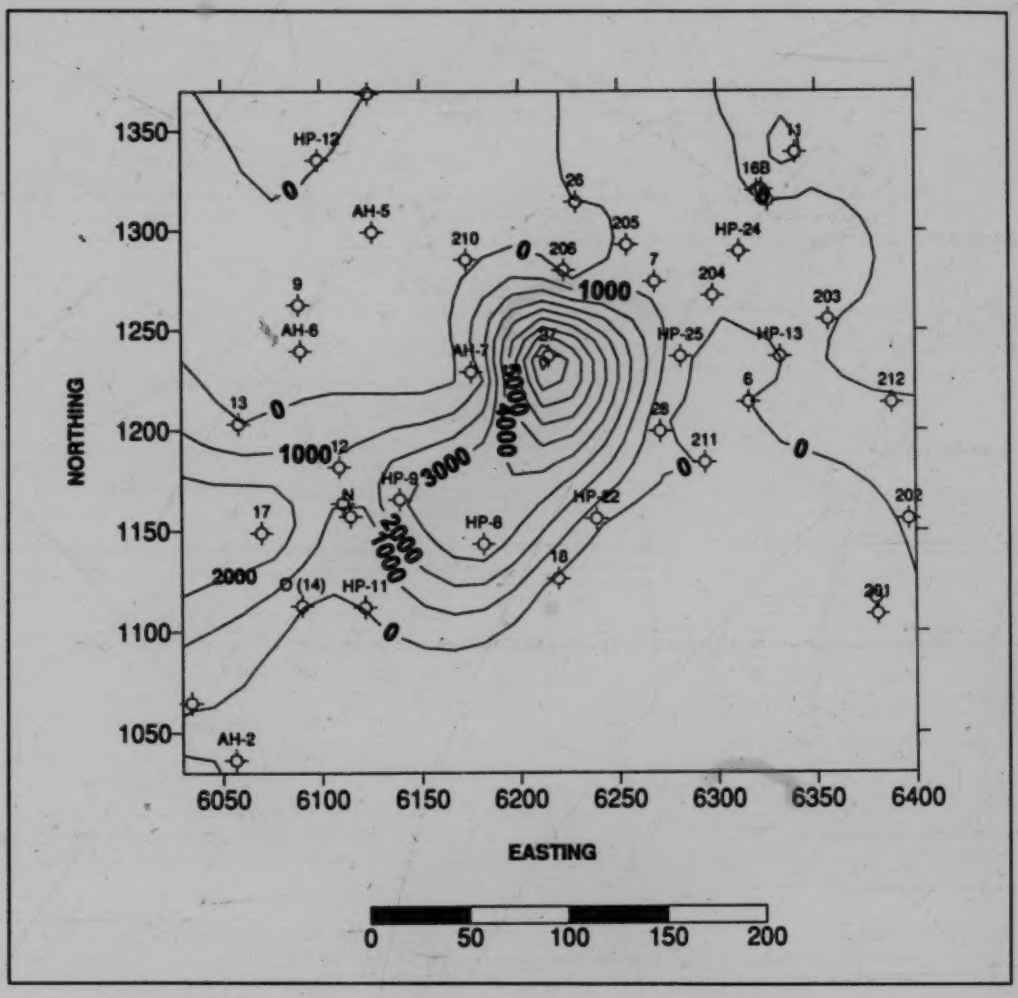


Figure 27: Interpretative Groundwater Isopleth of 1,1,1-Trichloroethane (ppb)

The contaminant trends for 1,1-DCA are the opposite of those for TCA (Figure 28). DCA is not present within the source, but starts to appear close to AH-07. The concentrations increase in the north-easterly direction with peak concentrations at HP-24. Again, along the fringe of the plume, there are no discernible traces of DCA.

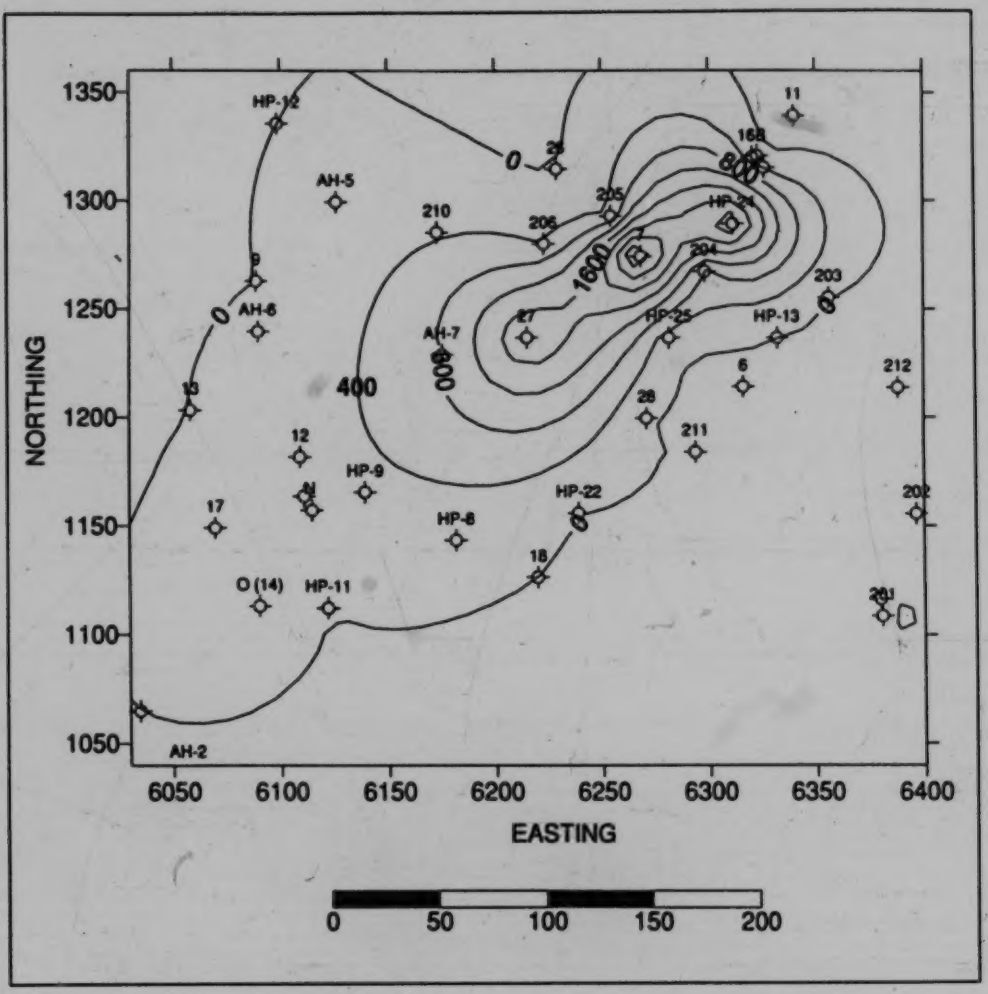


Figure 28: Interpretative Groundwater Isopleth of 1,1-Dichloroethane (ppb)

Although the water from the drainage ditch had a visible sheen, when it was analysed, results indicated non-detectable amounts of contaminants. Given these results, coupled with no detectable parent compound along the length of the outfall, it appears that the drainage ditch is not acting as a conduit for contamination from the old oil pit(s).

The isopleth contours of TCA coupled with those of DCA, support the theory of reductive dechlorination at cold temperatures, in that further downgradient there are decreasing concentrations of the parent compound (TCA) and increasing concentrations of the daughter compound (DCA). The above findings also suggest that there may be two sources, one previously delineated near wells 17 and 12, and a second near well 27.

7.0 MICROBIAL ANALYSIS

In addition to analysing microbial activity by measuring the different terminal electron accepting processes, microorganisms were enumerated using the Most Probable Number (MPN) technique. The intent was to determine whether a healthy, viable population of microorganisms existed in-situ despite the colder groundwater temperatures.

7.1 Microbial Enumeration: Most Probable Number (MPN)

The Most Probable Number technique is a method for estimating the number of viable microorganisms suspended in a liquid medium (Singleton and Sainsbury, 1993; Colwell, 1979; Walker and Colwell, 1975). The MPN method uses serial dilution in replicate test tubes containing a suitable liquid growth medium. The dilution itself is performed in a buffer that is created in separate vessels, and then inoculated into the corresponding serial dilution test tubes containing the specific medium. The first set of test tubes containing the medium is inoculated, in this case, with a fixed mass of soil. The next set of test tubes has an order of magnitude less concentration of soil mass than the previous set. Further sets of test tubes are similarly inoculated with progressively smaller soil masses. The test tubes are then incubated under the required conditions of temperature, oxygen, etc. Following incubation, each tube is examined for the presence or absence of growth (positive and negative scores, respectively), at set time intervals. In this study, scoring for positive and negative growth was done on a weekly basis.

Positive and negative scoring was assisted by the used of positive and negative controls. A positive control is a test tube with appropriate medium inoculated with a population of microorganisms known to be active. One can then compare the growth in the positive control to that of the actual MPN test tubes. The negative controls were a set of inoculated test tubes, prepared similarly as those for the MPN study, with the exception that they were sterilised by autoclaving.

The number of microorganisms in the original sample can be calculated from the pattern of positive and negative tubes using probability theory (statistical tables). Multiplying the result by the appropriate dilution factor then yields the MPN for that sample, (refer to Appendix J for sample calculations). It should be noted that the MPN calculated was per gram of dry soil. The dry weight calculations were conducted according to ASTM oven-drying dry weight calculations, (refer to Appendix J for dry weight calculations).

It should be noted that the MPN method has a low order of precision if few test tubes and dilutions are applied. For this reason seven dilutions were used with five replicates per dilution. Positive and negative controls were also used (medium inoculated with cultures yielding visible signs of growth and uninoculated medium). Confidence limits (95%) derived from MPN statistics were added to the results shown in Figures 29 and 30.

Five different classes of microorganisms were examined. The microorganisms enumerated and their corresponding media are summarised in Table 7. The recipes used for the media can be found in Appendix J. These specific classes were chosen for enumeration since they are known to degrade some of the contaminants of concern, (i.e. JP-4 degraders will degrade BTEX compounds) as well as create conditions conducive for reductive dechlorination (SRBs, NRBs and FeRBs). Total heterotrophs were enumerated to determine whether a healthy population of microorganisms existed at the site and whether or not they were temperature sensitive. In addition, heterotrophic counts are useful for comparison with other published studies, which often only have heterotrophic data.

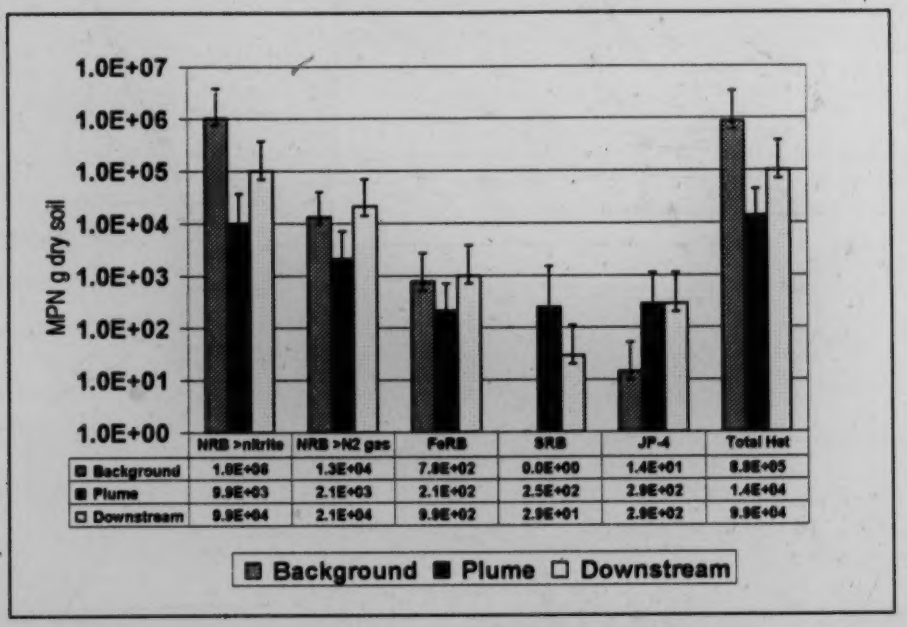
Table 7 : Microorganisms Enumerated for MPN Study

MICROORGANISM CLASS ENUMERATED	MEDIUM USED
Total heterotrophs	R2A liquid medium, full strength
JP-4 degraders	Bushnell-Haas plus 50 µL filter sterilised JP4
Sulfate-reducing bacteria (SRB)	Modified Butlin's with nails
Nitrate Reducing Bacteria (NRB)	Difco Nitrate broth with inverted Durham vials
Iron-reducing bacteria (FeRB)	B10 medium

Soil samples were taken from three different sites: one upgradient (AH-02), one within the plume (AH-07) and one downgradient (AH-17). To evaluate the potential for growth at colder temperatures, the samples were first incubated at 6°C for four weeks (scoring weekly for positive results), then incubated at 22°C for an additional two weeks and re-scored. A temperature of 6°C was chosen since it was believed to be representative of the in-situ temperatures at the site. It was later determined that in-situ groundwater temperatures were closer to 8°C (refer to Section 6.1).

Figures 29 and 30 show the MPN results after 4 and 6 weeks incubation, respectively. Detailed calculations and procedures for the analysis can be found in Appendix J, along with the tabulated results.

From these figures, it can be seen that a viable and healthy population of microorganisms exists as indicated by the total heterotrophic counts of 10^5 to 10^6/gram dry soil (Foght, 1999; Cookson, 1995). In proportion to the population of total heterotrophs, there are not many JP-4 degraders at the site, although the populations are in the same order of magnitude detected found in a previous study at a nearby site (Biggar, 1998). It should be noted that the number of JP-4 degraders is similar downstream and within the plume. This may be because only JP-4 degrading microorganisms were enumerated in this test, and the increased population downstream may not necessarily be using JP-4 as a substrate, but rather daughter products instead.

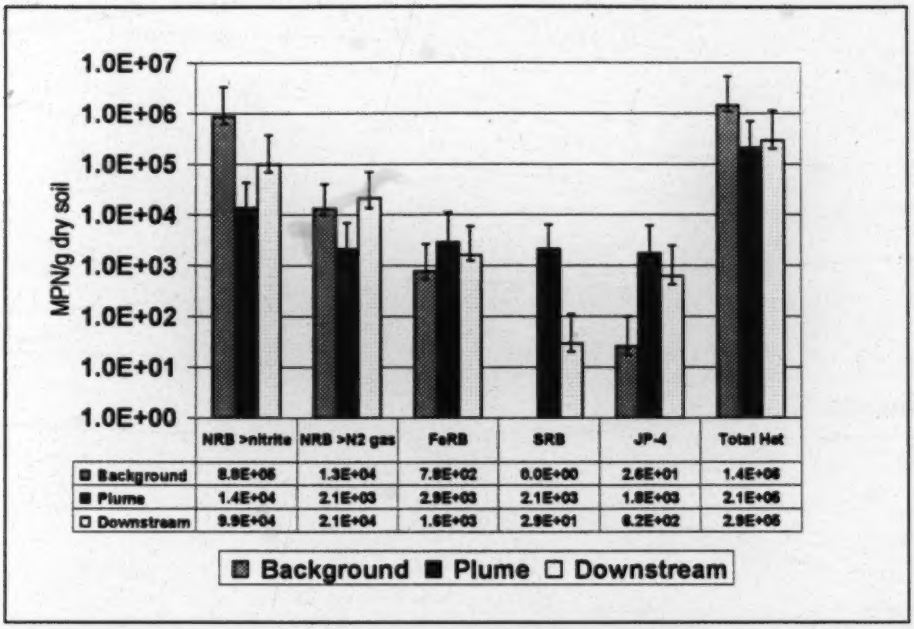


	NRB >nitrite	NRB >N2 gas	FeRB	SRB	JP-4	Total Het
Background	1.0E+06	1.3E+04	7.8E+02	0.0E+00	1.4E+01	8.9E+05
Plume	9.9E+03	2.1E+03	2.1E+02	2.5E+02	2.9E+02	1.4E+04
Downstream	9.9E+04	2.1E+04	9.9E+02	2.9E+01	2.9E+02	9.9E+04

NRB > Nitrite: nitrate reducing bacteria that produce nitrite
FeRB: iron-reducing bacteria
JP-4: JP-4 degrading bacteria
NRB > N_2 gas: nitrate reducing bacteria that produce N_2 gas
SRB: sulfate-reducing bacteria
Total Het: total heterotrophic bacteria

Figure 29: MPN Results – After 4 Weeks Incubation at 6°C

Foght (1999) suggested another explanation for the limited JP-4 degrading population. The site is visibly anaerobic (based on geochemistry findings), yet the JP-4 MPN test tubes were conducted aerobically. This geochemical discrepancy may account for the limited growth observed in the test tubes, ie. it is believed that the predominant JP-4 degraders in that area are anaerobic. This would also correspond to the low DO concentrations found in the plume, yet decreased BTEX contaminant concentrations.



	NRB >nitrite	NRB >N2 gas	FeRB	SRB	JP-4	Total Het
Background	8.9E+06	1.3E+04	7.8E+02	0.0E+00	2.6E+01	1.4E+06
Plume	1.4E+04	2.1E+03	2.9E+03	2.1E+03	1.8E+03	2.1E+05
Downstream	9.9E+04	2.1E+04	1.6E+03	2.9E+01	8.2E+02	2.9E+05

NRB > Nitrite: nitrate reducing bacteria that produce nitrite
FeRB: iron-reducing bacteria
JP-4: JP-4 degrading bacteria

NRB > N_2 gas: nitrate reducing bacteria that produce N_2 gas
SRB: sulfate-reducing bacteria
Total Het: total heterotrophic bacteria

Figure 30: MPN Results – After Additional 2 Weeks Incubation at 22°C

The dominant types of microorganisms appear to be nitrate and nitrite reducers; from 10^3/g within the plume, to 10^6/g upgradient. The discrepancy between the MPN results and the apparent lack of nitrate/nitrite in the groundwater at the site suggests that the site is likely nitrate deficient and as a result the nitrate/nitrite reducers are currently using another electron acceptor. This is likely since these types of microorganisms are usually facultative, (can respire using oxygen or nitrate as a TEA). As a result, they proliferated under conditions conducive for growth, such as during the MPN study.

Iron reducing microorganisms were found in lower numbers (ranging from 10^2 to 10^3), in comparison to the total heterotrophs at the site. As depicted in Figure 25, it can be seen that an iron reducing zone clearly exists in the centre of the delineated anaerobic area. This is evident through the high concentrations of ferrous iron in the plume compared to background levels. One possible explanation for this observation is

that the FeRB in the field produced all the Fe^{2+} possible (i.e. reduced all of the ferric iron available thus depleting it as a substrate), and therefore are in a *starved* condition. It is therefore possible that a viable population of FeRB capable of degrading the chlorinated aliphatic hydrocarbons and/or BTEX exists in the plume.

Geochemical results suggest that sulfate-reducing bacteria exist, or existed at the site, however MPN results show reduced populations of sulfate-reducing bacteria in comparison to total heterotrophs, JP-4 degrading bacteria and nitrate/nitrite reducing bacteria. Although, it should be noted that of four attempts to culture the SRBs at nearby sites (Biggar, 1998; Johns, 1999), this investigation was the only successful one. One possibility is that sulfate-reducing bacteria are not indigenous to the site, an observation that should be verified. The low numbers of SRBs could also be due in part to the high chloride concentrations in the groundwater (refer to Section 3.3.2), since high salt conditions can be inhibitory to certain sulfate-reducing bacteria (Postgate, 1984).

Comparing Figures 29 and 30, it can be seen that the results are similar at both 6°C and 22°C. The most significant changes (usually up to one order of magnitude) with the temperature increase occurred with the JP-4 degraders and the total heterotrophs. The other types of microorganisms enumerated had little to no increase in population with the temperature change. These findings suggest that the indigenous population of microorganisms may not be as sensitive to low temperatures as literature states and may be adapted to the cold in-situ temperatures. However, separate microcosm rate studies at colder temperatures will have to be conducted to verify this finding.

8.0 COMPUTER MODELING

8.1 BIOCHLOR

Groundwater Services Inc developed the screening tool BIOCHLOR for the Air Force Centre for Environmental Excellence (AFCEE) Technology transfer Division at Brooks Air Force Base. The mathematical technique to solve the coupled reactive transport equations used in the model was developed by researchers at the Batelle Pacific Northwest National Laboratory.

BIOCHLOR is a screening model that simulates remediation by natural attenuation of dissolved solvents at chlorinated solvent release sites. The software is programmed in Microsoft© EXCEL and is based on the Domenico analytical solute transport model with Martin-Hayden and Robbins (1997) improvements. It has the ability to simulate 1-dimensional (1-D) advection, 3-D dispersion, linear adsorption and biodegradation via reductive dechlorination. Reductive dechlorination is assumed to occur under anaerobic conditions and solvent degradation is assumed to follow a sequential first order decay process. This means that a parent compound undergoes first order decay to produce a daughter product and that product undergoes first order decay and so on.

The model assumes that degradation reactions occur only in the aqueous phase. BIOCHLOR evaluates centreline concentrations at $y = 0$, $x = 0$ to $x = L$ and the 2-D array at $z = 0$. There are three model types that can be simulated with the software. They are: 1) solute transport with no decay; 2) solute transport with sequential first-order decay in a plume defined by one rate of biodegradation zone; and 3) solute transport with sequential first-order decay in a plume defined by two different rates of biodegradation in separate zones. The three main assumptions of the model are:

1. The aquifer and flow field are homogeneous and isotropic;

2. The groundwater velocity is fast enough that molecular diffusion in the dispersion terms can be ignored; and
3. Adsorption is a reversible process represented by a linear isotherm.

The model equations, boundary conditions and limitations can be found in the BIOCHLOR manual (1999).

8.2 BIOCHLOR Sensitivity Analysis

Input parameters for BIOCHLOR include seepage velocity, adsorption, simulation time, modelled area length and width, source data, longitudinal, transverse and vertical dispersivity and biodegradation rate. In order to determine how some of these parameters affected the solution (sensitivity analysis), a factorial design was conducted on dissolved phase TCA. The design for the factorial is summarised in Table 8; details can be found in Appendix L.

Table 8 : Factorial Design Parameters

Parameter	-	+	Comments
Longitudinal Dispersivity (m)	1 (3.28ft)	100 (300ft)	Range as recommended by Mendoza, 1999
Transverse Dispersivity (m)	0.01 (0.03ft)	0.1 (0.3ft)	Range as recommended by Mendoza, 1999
Vertical Dispersivity (m)	1×10^{-99}	0.1 (0.3ft)	Range as recommended by Mendoza, 1999
Biodegradation Rate (yr^{-1}) for TCA	0.23	2.00	Low end from Howard et al., 1991. High end from Wiedemeier et al., 1999.

It should be noted that at the time of computer modelling, field biodegradation rates were not available. As a result, a range of literature values were used in the final analysis, which is discussed later.

The input parameters that were held constant for the model were seepage velocity, adsorption, simulation time, modelled area length and width and source data. The maximum field scale seepage velocity was approximately 119 m/yr (364 ft/yr), and was used as a conservative estimate. A value of 1.0 was chosen for the retardation factor. Again, this is conservative, since a small amount of soil organic matter (SOM) was

present in the aquifer. Based on 0.0056% SOM, a soil bulk density of 2.2 kg/L, an effective porosity of 0.34 and a partition coefficient of 183 L/kg (Howard et al., 1991) the retardation factor for TCA should be 2.0. A simulation time of 5 years was chosen, (refer to Section 8.3, discussion of time to reach steady state).

A single planar source was chosen, as opposed to a spatially varying source. In the former, a constant contaminant concentration is input for the entire width of the source, which yields the most conservative centreline concentration profiles. However, a spatially varying source is more accurate in terms of modelling field conditions. A spatially varying source was used in the final analysis, (discussed in Section 8.3). The modelled source width was 2.4m (8ft), although a plume width of 305m (1000ft) was chosen. The modelled plume length was 914m (3000ft), although the actual length is approximately 250m (762ft). These larger values for the plume dimensions are again conservative estimates. Although there appear to be two sources at the site, (one near well 17 and the other near well AH-07), the model was limited in its capability to simulate this situation. As a result, it was decided to model the site as one source emanating from AH-07. Therefore source concentrations of 9.4, 2.0 and 0.1 mg/L for TCA, DCA and CA respectively were based on field data near well AH-07. BIOCHLOR assumes that the distribution of source concentrations is applied over a fixed length and depth, which is infinitely thin in a plane perpendicular to groundwater flow, (Figure 31).

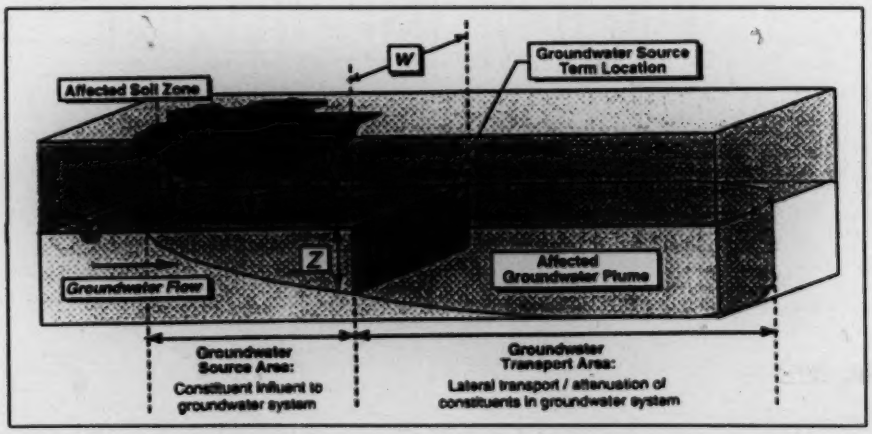


Figure 31: Schematic Distribution of BIOCHLOR Source (adapted from Aziz et al., 1999).

From the sensitivity analysis, it was found that all four of the factors varied had significant effects on the output, although the longitudinal dispersivity had the most pronounced effect on the output, (refer to Figure 32). Statistical significance was based on the normal probability plot and the analysis of variance. The normal probability plot shown in Figure 32 is the absolute value of the regression coefficient associated with each factor versus the corresponding normal probability (taken from statistical tables). The normal probability plot is another method of identifying whether a data set is normally distributed.

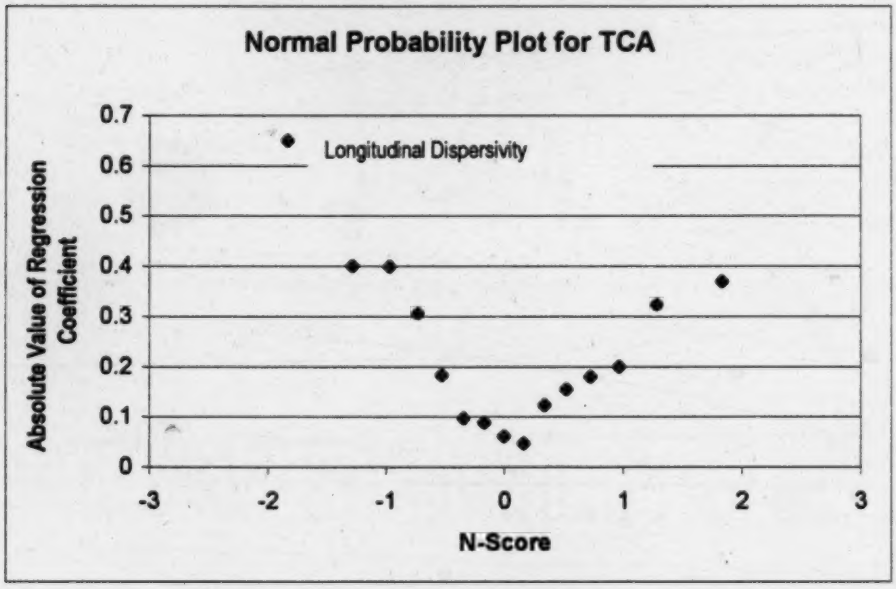


Figure 32: Normal Probability Plot for TCA

It should be noted that since all of the contaminant appears to be confined in the upper sand layer (i.e. the clay till seems to be acting as an effective barrier for vertical contaminant migration), 1×10^{-99} m is a more reasonable value for the vertical dispersivity, (i.e. no vertical dispersivity).

It was more difficult to bound the longitudinal and transverse dispersivities. Selection of dispersivity values is a difficult process, given the impracticality of measuring dispersion in the field (Fetter, 1992). Gelhar et al.

(1992) have compiled field dispersivity data from over 50 sites. The empirical data indicated that longitudinal dispersivity, in units of length, is related to scale (the distance between the source and the measurement point). They however, concluded that there is a considerable range of dispersivity values at any given scale (approximately 2-3 orders of magnitude). For the purpose of this study, a crude estimation of dispersivities was based on an electromagnetic survey conducted during the Royal Roads investigation (1991) of the chloride plume emanating from the salt storage building (Building 195). From the EM results one can see that the plume length is approximately four times greater than the plume width, (refer to Appendix K). The dimensions of the plume can be used for estimating the longitudinal and transverse dispersivities, however this should be further investigated. This can be achieved by using a 2-D model o simulate the chloride plume. All parameters should be held constant with the exception of the dispersivities which should be varied until the simulated plume models the chloride plume reasonably well.

8.3 BIOCHLOR Results

As a result of the limited field data, required as input for BIOCHLOR, three possible scenarios were investigated. These cases are summarised in Table 9.

Table 9 : Description of Three Possible Field Cases

CASE	SEEPAGE VELOCITY (m/yr)	LONGITUDINAL DISPERSIVITY (m)	TRANSVERSE DISPERSIVITY (m)	VERTICAL DISPERSIVITY (m)	BIODEGRADATION RATE (yr^{-1})
Worst	100	100	0.1	1×10^{-99}	0.23
Best	30	1	0.01	1×10^{-99}	2.00
Expected	50	1	0.01	1×10^{-99}	1.00

For the above cases a simulation time of 5 years was chosen, (discussed later in this section). As opposed to the sensitivity analysis discussed earlier, a spatially varying source was used instead of the single planar source. In the spatially varying option, the user may enter up to three concentrations with corresponding widths (Figure 33). Y_1 to Y_3 correspond to the widths of the three different concentration zones, and C_1 to C_3 correspond to the respective concentrations for the zones, C_1 being the highest concentration. For the

three cases, the widths and concentrations used for the source are shown in Table 10. The modelled area width and length were 304 m (1000 ft) and 914 m (3000 ft) respectively. The source thickness in the saturated zone was 2.4 m (8 ft).

Complete analysis of the dissolved contaminant concentrations along the plume centreline for the three cases can be found in Appendix L.

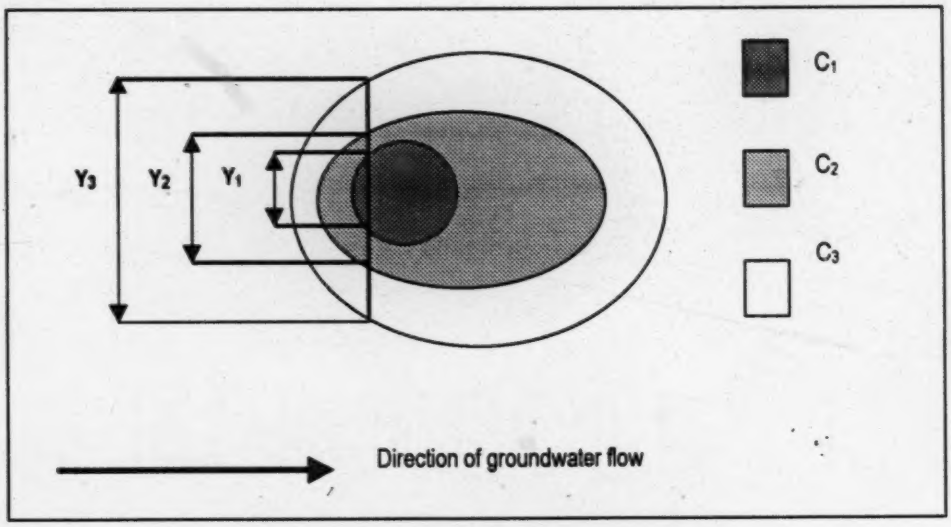


Figure 33 : BIOCHLOR Spatially Varying Source

Table 10 : Source Dimensions

WIDTH (m)		CONCENTRATION of TCA (mg/L)	
Y_1	20	C_1	9.4
Y_2	60	C_2	6.0
Y_3	100	C_3	0.6

Referring to the worst case, (assuming that dispersivities and seepage velocity are the dominant processes governing contaminant loss downgradient), one can see that the "no biodegradation" curve (NBC) and the

biodegradation curve (BC) nearly collapse on one another for TCA, (Figure 34). This shows that biodegradation is not the dominant process at the site under these conditions. One can also see that in the 5 year time span, the plume has travelled the length of the modelled area 914m (3000 ft). Contaminant concentrations drop off significantly at 91m (300 ft). However, the apparent reduction is a result of high dispersivities. The above observations also hold true for the DCA curve, (Figure 35).

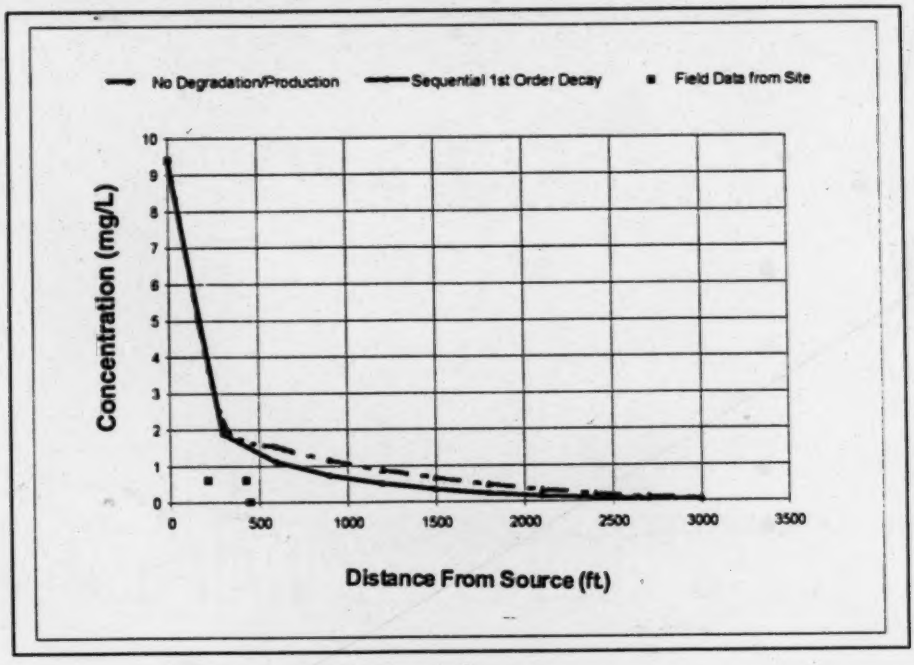


Figure 34: BIOCHLOR Worst Case for TCA

It should be noted that both the biodegradation and no-biodegradation curves for TCA over-estimate the contaminant concentrations observed in the field. The opposite is true for the DCA curves.

Comparing the worst case to the best case for TCA (Figure 36), one can see a marked decrease in the plume's travel distance, from 914 m (3000 ft) to 183 m (600 ft). Contaminant concentrations at 91 m (300 ft) for the best case NBC are much higher (9.4 mg/L) than the observed concentration at 91 m (300 ft) in the worst case NBC (2.2 mg/L). One can also see in the best case scenario, that there is a distinct difference

between the NBC and the BC. In this scenario the BC appears to slightly under-estimate the contaminant concentrations observed in the field.

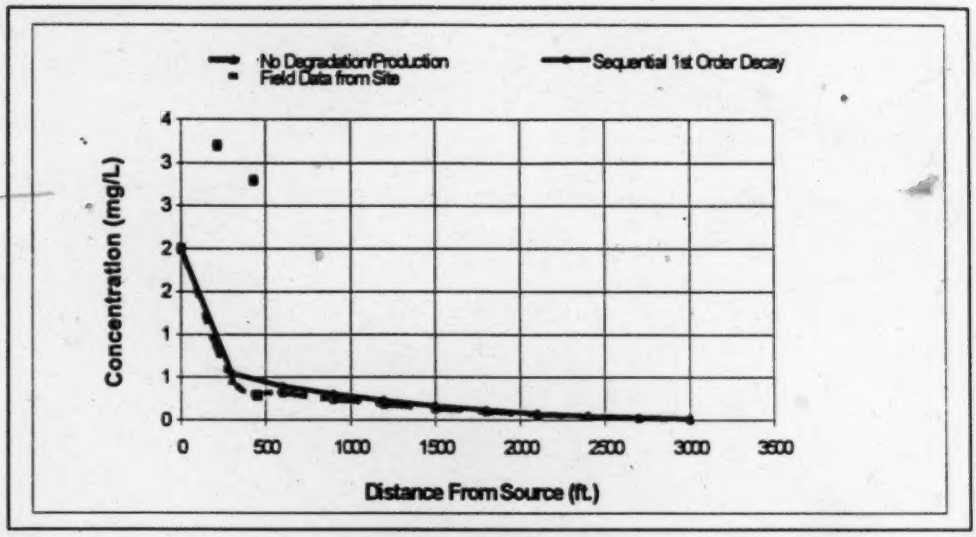


Figure 35: BIOCHLOR Worst Case for DCA

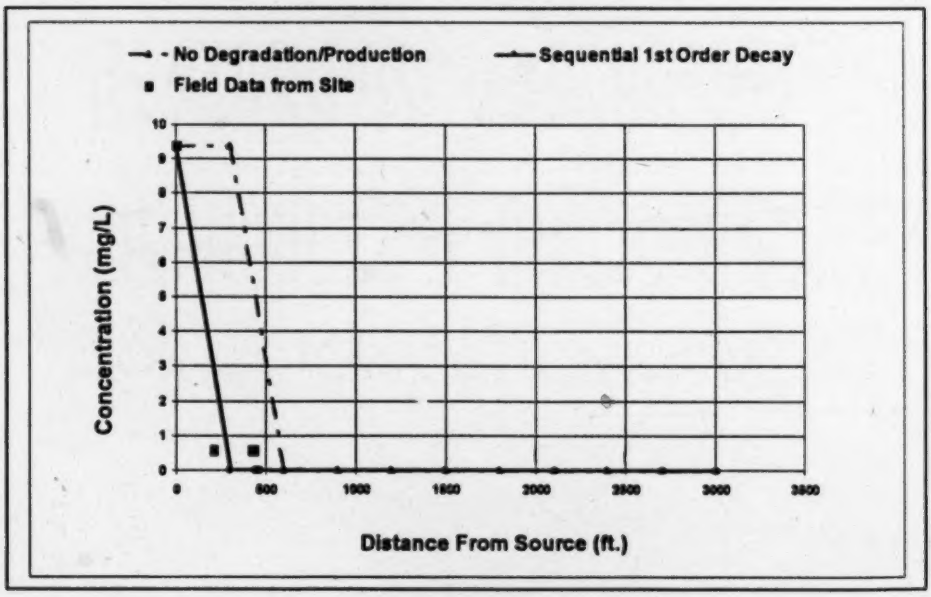


Figure 36: BIOCHLOR Best Case for TCA

in the same observations seen with the best case TCA, are observed with the best case DCA, (Figure 37). The travel distance of the plume has decreased from 914 m (3000 ft) to 91 m (300 ft). Similarly, the contaminant concentrations for the NBC at 91 m (300 ft) are much higher in the best case (2.0 mg/L) than the concentration at 91 m for the worst case (0.5 mg/L). This difference can be attributed to the much lower dispersivities used in the best case model.

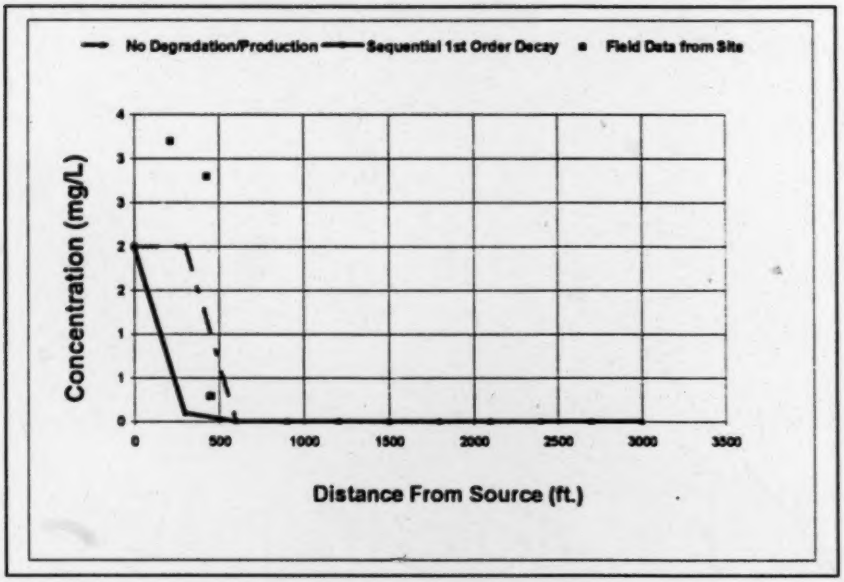


Figure 37: BIOCHLOR Best Case for DCA

Lastly when looking at the expected case (Figure 38), where the biodegradation rate (1.00 yr^{-1}) and seepage velocity 50 m/yr) are in the middle range one can see that the BC more closely resembles the field data. It can also be seen that with the slightly increased seepage velocity (in comparison to the best case) causes the plume to travel a greater distance downgradient. The same observations hold true for the expected case for DCA, (Figure 39). When a mid-range biodegradation rate (0.70 yr^{-1}) is chosen, the BC closely models the field data.

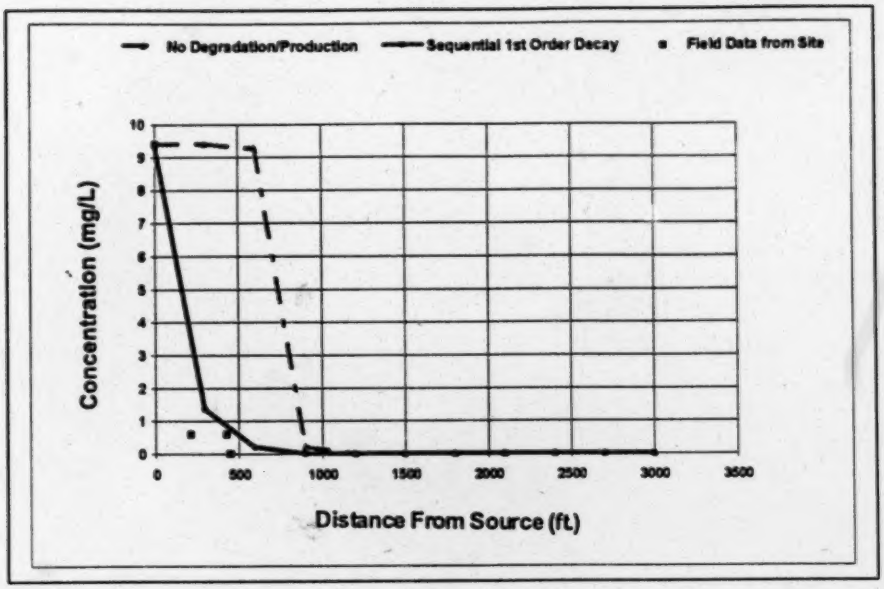


Figure 38: BIOCHLOR Expected Case for TCA

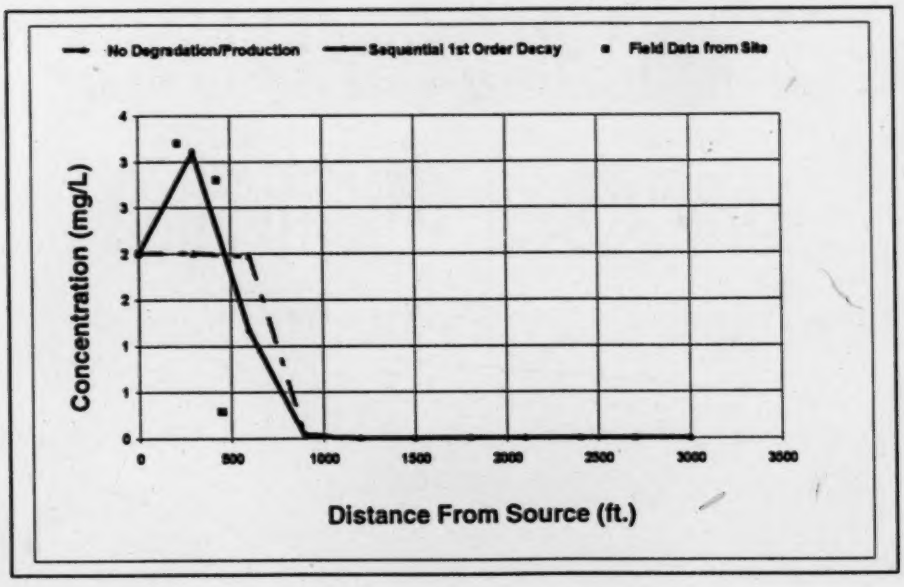


Figure 39: BIOCHLOR Expected Case DCA

The time at which steady state occurs was also investigated. This was accomplished by varying the simulation time in one year increments and determining when the contaminant curves had little to no variation in concentrations from one year to the next. This exercise was carried out for the best case. It was found that steady state for the BC occurred between 5 and 6 years. However, with the NBC it appeared that steady state would not occur. There was a continual downgradient migration of contaminant as simulation time increased. Since this is not what was observed in the field, (non-detectable amounts of contaminant at distances > 137m (450 ft), the model suggests that in order for the contaminant not to reach 91m (300ft), biodegradation should be occurring in the field.

From the above cases, it can be seen that the BC in the expected case models the field data reasonably well. Coupled with the steady state findings, there is evidence that biodegradation may be the dominant process governing contaminant reduction downgradient of the source, despite the cold temperatures. This phenomenon should however be further investigated by acquiring more downgradient field data and using a 2-D analytical model, (to be discussed in Section 10.0).

8.4 BIOCHLOR Limitations

There were two major limitations with the BIOCHLOR model that complicated the analysis. First, the model does a poor job in accurately defining a variable concentration source, (Figure 33). It assumes a perfectly symmetrical plume, which was not the case in the field. Thus, the centreline distance and concentrations calculated from the defined source may not be representative of the plume. This however, is a common drawback associated with two-dimensional models when applied to a three-dimensional problem. The second perceived difficulty was the model's sensitivity to longitudinal and transverse dispersivities. Since, representative dispersivities are unknown it was only possible to bound an expected range of values. Nonetheless, the conservative input values used in the expected case analysis should provide a reasonable approximation of how far the dissolved phase plume may migrate from the source.

9.0 DISCUSSION

Reductive dechlorination of the dissolved CAH plume emanating from the former landfill appears to be on going despite the colder in-situ temperatures. Evidence in support of this assertion is as follows:

1. Analysis of the terminal electron acceptors of dissolved oxygen, nitrate, sulfate, sulfide, ferric and ferrous iron and methane show sequential depletion of the TEAs as well as an increase in metabolic by-products through the contaminated zone, in the sequence anticipated;

2. The dominant TEAPs in the plume indicate that microbial activity is ongoing and that highly reduced conditions exist (which are conducive for both BTEX mineralisation and reductive dechlorination);

3. Analysis of BTEX in the groundwater indicates that the elevated concentrations observed in the contaminated zones are not being observed in significant quantities more than 150m downgradient;

4. Analysis of TCA in the groundwater indicates that the elevated concentrations observed in the contaminated zones are not being observed in significant quantities more than 150m downgradient;

5. Analysis of DCA in the groundwater indicates that there is little DCA near the source, but increasing concentrations further downgradient are observed;

6. The Most Probable Number analyses of the in-situ microbial population indicate that upgradient and downgradient from the contamination, a viable population of facultative bacteria exist that are active at cold temperatures. Within the contaminated zone, their exists a viable population of iron reducing bacteria and JP-4 degrading bacteria that are capable of degrading the chlorinated aliphatic and BTEX hydrocarbons, respectively;

7. Groundwater modelling at the site indicates that the anticipated travel distances of the detectable TCA and DCA contamination is less than 300 m with biodegradation, (which most closely represents field conditions). Without biodegradation of these compounds, the distances travelled are expected to be much greater.

Although seepage velocities across the site are rather high, (approximately 75 m/yr), there appears to be significant contaminant reduction downgradient from the source, as indicated above. Also, the results of the water analysis from the drainage ditch, coupled with no apparent parent compound found along the length of the outfall, indicate that the ditch is not acting as a conduit for contamination from the old oil pit(s) at the site. Therefore, despite the relatively cold groundwater temperatures, reductive dechlorination appears to be biodegrading the contaminants sufficiently so that the plume travel distance is relatively short.

A recent paper published by Wiedemeier et al., (1999) also describes twelve sites where reductive dechlorination is on-going despite a wide range of temperatures (between 9 and 26°). They concluded that the process of reductive dechlorination appeared to be temperature independent for the range of temperatures studied.

Despite the evidence indicating intrinsic bioremediation at cold temperatures is occurring at the site, there remains a level of uncertainty as to whether the site can be deemed suitable for closure using IB. Further investigation is still warranted in order to determine with a greater degree of certainty that reductive dechlorination is the dominant process at the site. From the modelling exercise it can be seen that the source must be better defined. As mentioned previously, the groundwater contaminant analysis indicates that there might be two separate sources, one near well 17 and 12, the other near well 27. Secondly, from the modelling it was evident that in order to accurately predict what was happening in the field, better centreline field data are needed. It is believed that there is an insufficient amount of downgradient data beyond well 16 in the bog.

The data sampled for this study were heterogeneous in that not all of the same wells were sampled during each field investigation. There should be more consistency in future sampling programs. The same wells should be sampled each time to give a more accurate temporal set of data. It would also be useful if more sample intervals were implemented, giving a more accurate long-term picture of what is occurring at the site. Also related to field data acquisition is the issue of dispersivities. The use of the EM survey (RRMC, 1991) as a tool for determining the longitudinal and transverse dispersivities should be further investigated with a two-dimensional model as opposed to a one dimensional model such as BIOCHLOR. Although the slug tests and subsequent permeameter tests yielded similar hydraulic conductivities at the site, it would be prudent to carry out more slug tests on wells where the well screen falls below the water table.

Finally, an unresolved issue from the microbial enumeration relates to the results from the MPN analysis of SRB. Laboratory MPN analysis show little to no SRB present, yet there has been definite reduction of sulphate in the groundwater within the plume. It is possible that high chloride concentrations in the groundwater are toxic to the SRB, or that some other mechanism is responsible for the reduction of sulfate in the groundwater. Alternately, because SRB are difficult to culture, their absence in the lab may not preclude their presence in the field. This could be further investigated by changing the sampling and/or handling techniques, but is not necessary to further prove intrinsic bioremediation at the site.

9.1 Risk to Receptors

At present, there are no drinking water wells in the vicinity, thus reducing the risk to humans through direct consumption of contaminant. However, as previously mentioned, there are two other possible environmental risks to receptors for this site:

1. Introduction of contaminant into Marie Creek which eventually flows in the Beaver River; and
2. Contaminant uptake by vegetation in the area.

Groundwater and sediment sampling downgradient of the plume, in the bog and near Marie Creek indicate no detectable amounts of contaminant. Therefore at this time, there appears to be no environmental risk to receptors from the contaminant plume. Hence, risk to receptors from the contaminant plume is deemed low.

10.0 CONCLUSIONS AND RECOMMENDATIONS

By reviewing the previous studies conducted at the site, and analysing the field and microbial data coupled with the computer modelling several conclusions can be made with regards to intrinsic bioremediation at the site.

The local stratigraphy consists of 4 distinct layers: an organic layer, a silty sand layer, a clay till layer and finally another silty sand layer. The respective depths to the base of each layer are: 0.1 – 0.6m; 1.5 – 2.5m; 11m and an unknown depth. The upper water table lies at a depth of approximately 2.5m and the lower water table slightly below 11m; both are unconfined. Local groundwater flow is in the north-easterly direction, (also confirmed by the 1 CEU, Royal Roads and An-Geo reports). The expected gradient across the site is in the order of 1.1×10^{-2}, with an expected hydraulic conductivity of approximately 7.5×10^{-5} m/s. This results in an expected seepage velocity of approximately 76 m/yr, (refer to Table 6).

There is significant evidence for the intrinsic bioremediation of chlorinated hydrocarbons and BTEX mineralisation at the site despite the cold groundwater temperatures. This includes:

- Geochemical evidence of depleted terminal electron acceptors and enriched products of microbial degradation in the groundwater across the site;

- Adequate supply of electron donors at the site (i.e. BTEX);

- Decreasing concentrations of dissolved BTEX and TCA downgradient from the source area(s);

- Increasing concentrations of dissolved DCA (daughter product) downgradient from the source area(s);

- Enumeration of significant populations of: total heterotrophic, nitrate/nitrite reducing, iron reducing and JP-4 degrading microorganisms upgradient and downgradient of the plume and in the plume itself; and

- Groundwater modelling at the site indicates maximum travel distances of less than 300m for the contaminants if intrinsic bioremediation is ongoing. Without biodegradation of these compounds, the distances travelled should be much greater.

Although there is no apparent risk to receptors, coupled with the considerable evidence for reductive dechlorination at the site, there are a number of unresolved issues that should be further investigated in order to conclusively state that intrinsic bioremediation is a viable remediation option at the site. Recommendations include:

1. The source and plume must be properly delineated. This would involve determining whether two (or more) sources exist, one near wells 17 and 12 the other near well 27. This could be accomplished by augering until the clay till, and analysing the sand right above the clay till for free-product since this where it would more than likely reside if a second source existed. The lateral extent of the plume should be further refined to accurately model the centreline in a two-dimensional model. Increased downgradient data are also required, (i.e. past well 16), again to create a more accurate picture of what is occurring at the site;

2. Consistent (same wells sampled at each sampling period) and continued long-term monitoring is needed to fully understand what processes are taking place at the site;

3. The electromagnetic survey conducted in 1991 should be further used in conjunction with a two-dimensional model to estimate the longitudinal and transverse dispersivities at the site; and

4. The storm drain should be tested, cleaned and visually examined.

With respect to item four, a visual inspection of the sewer system at the site, using a mobile camera was attempted (refer to 4.0 Field Investigation) but was unsuccessful due to an excess of sediment in the storm drain. However, visual inspection is still recommended after the sediment is removed. Prior to the removal of the sediment it is prudent to analyse it for chlorinated aliphatic hydrocarbons and BTEX contamination to ensure that the data interpretation reported herein has not overlooked anything. It is also suggested that the site cannot be deemed suitable for intrinsic bioremediation until points one and two are completed.

10.1 Remediation Options

Remedial action should ensure that no significant contamination reaches the wooded area downgradient of the bog and Marie Creek. This can be accomplished by:

1. Not proceeding with an active remedial strategy, since there appears to be no risk to the receptors and the plume does not to appear to be travelling beyond 300m. This is predicated on the assumption that sufficient data are collected during future sampling to ensure that the site is adequately characterised;

2. Gathering more temporal data, as discussed in Section 10.0; and

3. Implementing a funnel and gate system if further analysis indicates intrinsic bioremediation is not viable.

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APPENDIX A:

Purged Groundwater Indicators
And
Sample VOC Trace

Purged Groundwater Indicators

Site: _____

Well ID Number: _____ **Date:** _____

Depth of sampling port: _____ **Operator:** _____

Sampling Method: _____ **Weather:** _____

Time Start Purge: _____ **Time End Purge:** _____

Purge Rate (LPM): _____ **Time Sampled:** _____

Well Pipe Diameter: _____ **Depth to Water** (m, top of pipe): _____

Well Water Volume (L): _____ **Downhole D.O.** (mg/L) _____

Indicator										
Volume (L)										
Time (min)										
Temperature ^{0}C										
pH ±0.01										
Conductivity µS / mS										
D.O. mg/L										
eH mV										
Water Odour & Appearance										

CR=Clear CL=Cloudy GY=Grey BN=Brown SH=Strong Hydrocarbon odour MH=moderate WH=weak N=none

Samples taken:

_____ x _____	ml vials	for :	BTEX	Sample Label: _____
_____ x _____	ml vials	for :	VOC	Sample Label: _____
_____ x _____	ml vials	for:	Fe^{2+}	Sample Label: _____
_____ x _____	ml vials	for :	SO_4^{2-}	Sample Label: _____
_____ x _____	ml vials	for :	S^{2-}	Sample Label: _____
_____ x _____	ml vials	for :	NO_3/NO_2	Sample Label: _____
_____ x _____	ml vials	for :	CH_4	Sample Label: _____
_____ x _____	ml vials	for :	Cl^-	Sample Label: _____
_____ x _____	ml vials	for :	Alkalinity	Sample Label: _____
_____ x _____	ml vials	for :	TOC	Sample Label: _____
_____ x _____	ml vials	for :	TEH/TVH	Sample Label: _____
_____ x _____	ml vials	for :	Nutrients	Sample Label: _____

Notes:

Free Product thickness = _____

_____

_____

Screened

June 98

WELL SITE	PARAMETER				
	DO	Temp	pH	Cond	Redox
	mg/L	°C		mS/uS	mV
4	8.04	10.1	6.78	487	-15.1
16A	6.85	8.6	7.95	317	-64.9
17	6.76	16.5	6.63	671	8.6
18	6.9	13.6	6.01	4.25	
27	17	6.6	6.11	2.8	-20.6
28	1.43	16.2	6.84	1469	-2.5
202	7.83	13.6	6.04	419	-17.3
205	3.67	7.3	6.65	824	8.2
206					
211	7.8	8	6.13	252	-13.2
Average	7.4	11.4	6.6	494	-15
min	1.4	7.3	6.0	3	-65
max	17.0	16.5	8.0	1469	9

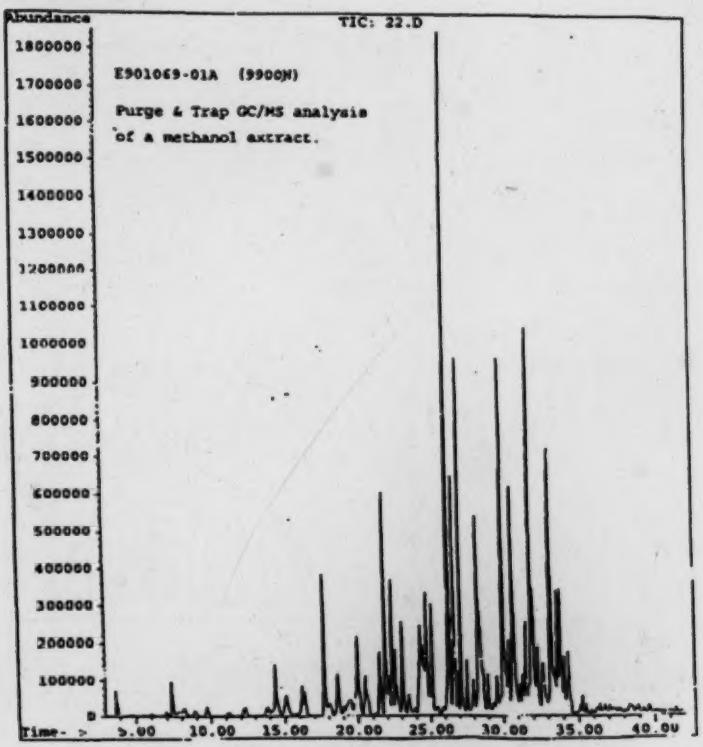
August 98

WELL SITE	PARAMETER				
	DO	Temp	pH	Cond	Redox
	mg/L	°C		mS/uS	mV
HP-05	6.6	18	6.95	372	-48
HP-06	1.96	17	5.66	375	-43
HP-07	1.6	17.1	6.2	1010	-42
HP-08	<1				
HP-09	<1				
HP-10	1.24	17.1	7	388	-40
HP-11	1.06	18	6	750	
HP-12	0.85	17.4	5.8		
HP-13	0.12	14.3	6.9		
HP-14		15.5	7	800	
HP-15	<1	18	6.8	1080	
9	1.5	14.5	7.1	415	-35
12	0.6	18	6.6	1297	-43
17	0.8	17	6.75	1665	-41
26	1.3	9.7	6.6	544	-38
27	0.9	11.8	6.76	4920	-25
28	0.7		6.3	5750	-19
203	1	8	6.3	165	-28
207	0.4	13.4	7	694	-70
608	4.6	13.3	6.5	98	-30
AVE	1.6	15.2	6.6	1270	-39
MIN	0.1	8.0	5.7	98	-70
MAX	6.6	18.0	7.1	5750	-19

October 98

WELL SITE	PARAMETER				
	DO	Temp	pH	Cond	Redox
	mg/L	°C		mS/uS	mV
AH-07	1.25	12.4	6.75	10960	
HP-21	7.98	9.1	7.16	267	
HP-23	1.77	6.7	7.17	1029	
HP-24	1.41	6.5	7.07	6330	
HP-25	1.42	9.3	6.97	9100	
204	0.92	9.6	6.85	4890	
206	5.75	9.4	6.98	978	
Average	3.2	8.4	7.0	3766	
min	0.9	6.5	6.9	267	
max	8.0	9.6	7.2	10960	

File : C:\HPCHEM\1\DATA\01.13\22.D
Operator :
Acquired : 14 Jan 99 5:18 am using AcqMethod PNT8240
Instrument : 5970 - In
Sample Name: E901069-01 (100uL)
Misc Info : 10uL IS/Surr
Vial Number: 22



APPENDIX B:

Borehole Logs

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET — HOLE NO. 1

PROJECT: CFB Cold Lake Environmental Study — PROJECT NO. 89-CEU-31

SITE OR SECTION:
LOCATION: Borehole #1
RIG: Nodwell

SHEET 1 OF 1
DATE DRILLED 9/8/89
LOGGED BY TG
HOLE SIZE 12.7 cm

Depth (m)	Elev. & Water	Unified System	Soil Profile	SOIL DESCRIPTION (Surface –)	Unconfined compressive strength (K.S.F.) 2 4 6 8 10 / (kPa) 100 200 300 400 500	Water content (%) 5.0 10.0 15.0 20.0	P.L. W L.L. 25.0 30.0 40.0	Type	Sample No.	Blow/ft. (0.3m) or Recovery	Other Tests (see codes)
1.5				0–.762 m medium/coarse sand						26	
3.1										3	
4.6				2.29 m saturated silty clay water table @ 2.25 m						9	
6.1										5	
7.6				5.33 m medium/highly plastic clay						12	
9.1				8.38 m silty clay with #10 size aggregate till						12	
10.7				9.91 m medium/highly plastic clay						20	
12.2										19	
13.7				12.96 m silty clay till scattered ¾" aggregate						22	
15.2										9	
16.7				15.24 m sand lens						87	
18.3				16.0 m stiff clay till scattered ¾" aggregate						73	
19.8										64	
21.3										Refusal	
22.9										57	
				22.1 m bottom of hole							

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 2

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #2

SHEET 1 OF 1

DATE DRILLED 10/8/89

LOGGED BY TG

RIG Nodwell

HOLE SIZE 12.7 cm

Depth (m)	Elev. & Datum	Unified System	Soil Profile	SOIL DESCRIPTION	unconfined compressive strength (K.S.F.) 2 4 6 8 10 / 100 200 300 400 500 (kPa) / water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0 / P.L. W L.L.	Type	Sample No.	Blow/Ft. (0.3m) or Recovery	Other Tests (see codes)
				Surface -					
1.5			/	0-.762 m medium/coarse sand				20	
3.1			/	2.29 m stiff clay				8	
			/	2.7 m bottom of hole					
4.6									
6.1									
7.6									
9.1									
10.7									
12.2									
13.7									
15.2									
16.7									
18.3									

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET — HOLE NO. 3

PROJECT CFB Cold Lake Environmental Study — PROJECT NO. 89-CEU-31

SITE OR SECTION
LOCATION Borehole #3

SHEET 1 OF 1
DATE DRILLED 10/8/89
LOGGED BY TG
RIG Nodwell
HOLE SIZE 12.7

unconfined compressive strength (K.S.F.) 2 4 6 8 10
100 200 300 400 500 (kPa)
water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0
P.L. W L.L.

Depth (m)	Elev. & Water	Unified System	Soil Profile	SOIL DESCRIPTION	Type	Sample No.	Blow/ft. (0.3m) or Recovery	Other Tests (see code)
				Surface -				
1.5				.762 m fine sand			17	
3.1				2.29 m fine sand			17	
4.6				3.8 m fine sand with some coarse particles			51	
6.1				5.32 m fine sand			39	
7.6				6.9 m fine sand with one ¾" stone			33	
9.1				watertable 5.32 to 8.38 m			21	
10.7				8.38 m coarse sand sat'd traces of oxidation clay interface @ 31'0"			47	
12.2				9.91 m stiff clay with scattered #10 size agg. till			42	
13.7				11.4 m stiff clay with scattered #10 ¼"+3/8" agg. till			44	
15.2				12.96 m stiff clay with scattered ¼"+3/8" agg. till			42	
16.7				14.48 m stiff clay scatt. ¼" agg. some water encou.			53	
18.3				15.8 m staff clay water present			97	
19.8				17.52 m stiff clay scatt. #10 agg. Hit rock - only 22.8 cm recovery			90	
21.3				19.1 m no recovery			104	
22.9				20.6 m stiff dry clay			112	
24.4				22.1 m stiff clay				

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET — HOLE NO. 4

PROJECT CFB Cold Lake Environmental Study — PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #4

SHEET 1 OF 1

DATE DRILLED 11/8/89

LOGGED BY TG

RIG Nodwell

HOLE SIZE 12.7 cm

Depth (m)	Elev. & Water	Drilled System	Soil Profile	SOIL DESCRIPTION	unconfined compressive strength (K.S.F.) 2 4 6 8 10 / 100 200 300 400 500 (kPa) — water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0 — P.L. N L.L.	Type	Sample No.	Blow/Ft. or Recovery	Other Tests (see codes)
				Surface -					
1.5				.762 m coarse sand damp					
3.1				2.29 m coarse sand wet					
			/	3.1 m clay strata					
4.6			/	3.2 m bottom of hole					
6.1									
7.6									
9.1									
10.7									
12.2									
13.7									
15.2									
16.7									
18.3									

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 5

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #5

SHEET 1 OF 1

DATE DRILLED 11/8/89

LOGGED BY TG

RIG Nodwell

HOLE SIZE 12.7 cm

Depth	Elev. & Datum	Drilling System	Soil Profile	SOIL DESCRIPTION	unconfined compressive strength (K.S.F.) 2 4 6 8 10 / 100 200 300 400 500 (kPa) / water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0 / P.L. W L.L.	Type	Sample No.	Blow/Ft (0.3m) or Recovery	Other Tests (see codes)
1.5				Surface -					
3.1				Water @ 1.8 m					
4.6				2.68 m coarse sand damp bottom of hole clay strata					
6.1									
7.6									
9.1									
10.7									
12.2									
13.7									
15.2									
16.7									
18.3									

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 6

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #6

RIG Nodwell

SHEET 1 OF 1
DATE DRILLED 11/8/89
LOGGED BY TG
HOLE SIZE 12.7 cm

Depth (m)	Elev. & Datum	Unified System	Soil Profile	SOIL DESCRIPTION
				Surface -
1.5				Water at 1.8 m
3.1				2.29 m fine sand sat'd
				2.43 m clay interface
4.6				2.44 m bottom of hole
6.1				
7.6				
9.1				
10.7				
12.2				
13.7				
15.2				
16.7				
18.3				

unconfined compressive strength (K.S.F.)
1 2 4 6 8 10
100 200 300 400 500 (kPa)
water content (%) P.L. W L.L.
5.0 10.0 15.0 20.0 25.0 30.0 40.0

Type | Sample No. | Blow/ft. (0.3m) or Recovery | Other Tests (see code)

5

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET — HOLE NO. 7

PROJECT: CFB Cold Lake Environmental Study — PROJECT NO. 89-CEU-31

SITE OR SECTION:
LOCATION: Borehole #7
RIG: Nodwell

SHEET 1 OF 1
DATE DRILLED 11/8/89
LOGGED BY TG
HOLE SIZE 12.7 cm

Depth	Sieve & Water	Unified System	Soil Profile	SOIL DESCRIPTION	Unconfined compressive strength (K.S.F.) / (kPa) / water content (%) / P.L. / W / L.L.	Type	Sample No.	Blow/Ft. (0.3m) or Recovery	Other Tests (see code)
				Surface -					
1.5									
3.1				1.5 m coarse sand * Water @ 1.67 m				11 7	
4.6				2.29 m grey coloured coarse sand** 2.43 m clay interface clay sample taken for analysis (CL-2)					
6.1									
7.6									
9.1				* oxide discolouration also grey sand with slight odour. Chemical analysis sample taken (CL-1)					
10.7									
12.2				**saturated					
13.7									
15.2									
16.7									
18.3									

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 8

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #8

RIG Nodwell

SHEET 1 OF 1
DATE DRILLED 12/8/89
LOGGED BY TG
HOLE SIZE 12.7 cm

Depth	Elev. & Water	Unified System	Soil Profile	SOIL DESCRIPTION	Unconfined compressive strength (K.S.F.) / (kPa) / water content (%) / P.L. W L.L.	Type	Sample No.	Blows/Ft. (0.3m) or Recovery	Other Tests (see codes)
				Surface -					
1.5				0-.762 m organics				7	
3.1				.762 m silty clay				19	
4.6				2.29 m silty clay				28	
6.1				3.81 m silty clay with scattered 3/8"-3/4" agg.				27	
7.6				5.3 m silty clay with scattered stones				28	
9.1				6.9 m coarse sand sat'd water @ 6.9 m				83	
10.7				8.38 m coarse sand sat'd clay interface 31'0"				28	
12.2				9.9 m silty clay-partial recovery - 10"				43	
13.7				11.4 m silty clay				64	
15.2				12.9 m silty clay with scattered ¼" stones				64	
16.7				14.4 m silty clay				87	
18.3				16.0 m silty clay with scattered stones. Small amt. of sand @ tip of split spoon				73	
				17.5 m silty clay with scattered ¼" stones				Refusal	

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 9

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #9

SHEET 1 OF 1

DATE DRILLED 14/8/89

LOGGED BY TG

RIG Nodwell

HOLE SIZE 12.7 cm

Depth m	Elev. & Water	Unified System	Soil Profile	SOIL DESCRIPTION Surface -	unconfined compressive strength (K.S.F.) 1 2 4 6 8 10 / 100 200 300 400 500 (kPa) / water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0 / P.L. W L.L.	Type	Sample No.	Blows/Ft. (N.Dm) or Recovery	Other Tests (see codes)
1.5			::	.762 m coarse sand					
3.1			::	water @ 0.91 m				21	
			::	2.29 m water put down hole					
4.6			/	coarse sand/silty clay				10	
6.1			/	clay interface @ 2.6 m					
7.6			/						
9.1									
10.7									
12.2									
13.7									
15.2									
16.7									
18.3									

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET — HOLE NO. 10

PROJECT CFB Cold Lake Environmental Study — PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #10

RIG Nodwell

SHEET 1 OF 1

DATE DRILLED 14/8/89

LOGGED BY TG

HOLE SIZE 12.7 cm

Depth (m)	Elev. & Datum	Drilling System	Soil Profile	SOIL DESCRIPTION	unconfined compressive strength (K.S.F.) / (kPa) — water content (%) — P.L. — W — L.L.	Type	Sample No.	Blow/ft. or Recovery	Other Tests (see codes)
				Surface -	2 4 6 8 / 100 200 300 400 500 / 5.0 10.0 15.0 20.0 25.0 30.0 40.0				
1.5			::	.762 m medium/coarse sand saturated water @ 2'-6'				15	
3.1			:						
4.6			/	2.29 m clay clay interface @ 2.13 m				10	
6.1			/						
7.6			/						
9.1			/						
10.7			/						
12.2			/						
13.7			/						
15.2			/						
16.7			/						
18.3			/						
			/						

No. 1 CONSTRUCTION ENGINEERING UNIT
TESTING LABORATORY

SOIL LOG SHEET

HOLE NO. 11

PROJECT CFB Cold Lake Environmental Study

PROJECT NO. 89-CEU-31

SITE OR SECTION

LOCATION Borehole #11

SHEET 1 OF 1

DATE DRILLED 14/8/89

LOGGED BY TG

RIG Nodwell

HOLE SIZE 12.7 cm

Depth (m)	Elev. & Datum	Unified System	Soil Profile	SOIL DESCRIPTION Surface -	unconfined compressive strength (K.S.F.) 2 4 6 8 10 100 200 300 400 500 (KPa) water content (%) 5.0 10.0 15.0 20.0 25.0 30.0 40.0 P.L. W L.L.	Type	Sample No.	Blows/ft. (0.3m) Recovery	Other Tests (see code)
1.5				.076 m organics .762 m silty sand - sat'd water @ .762 m till interface @ 1.82 m				5	
3.1				2.29 m silty till				13	
4.6				3.81 m silty till same as 2.29 m 5.3 m silty till same as 2.29 m				24 21	
6.1				6.9 m silty till				21	
7.6				8.4-8.5 m till				50	
9.1				8.44-8.76 m coarse sand 8.75-8.83 m till					
10.7									
12.2									
13.7 15.2									
16.7									

Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 12

PROJECT CFB Cold Lake Environmental Study

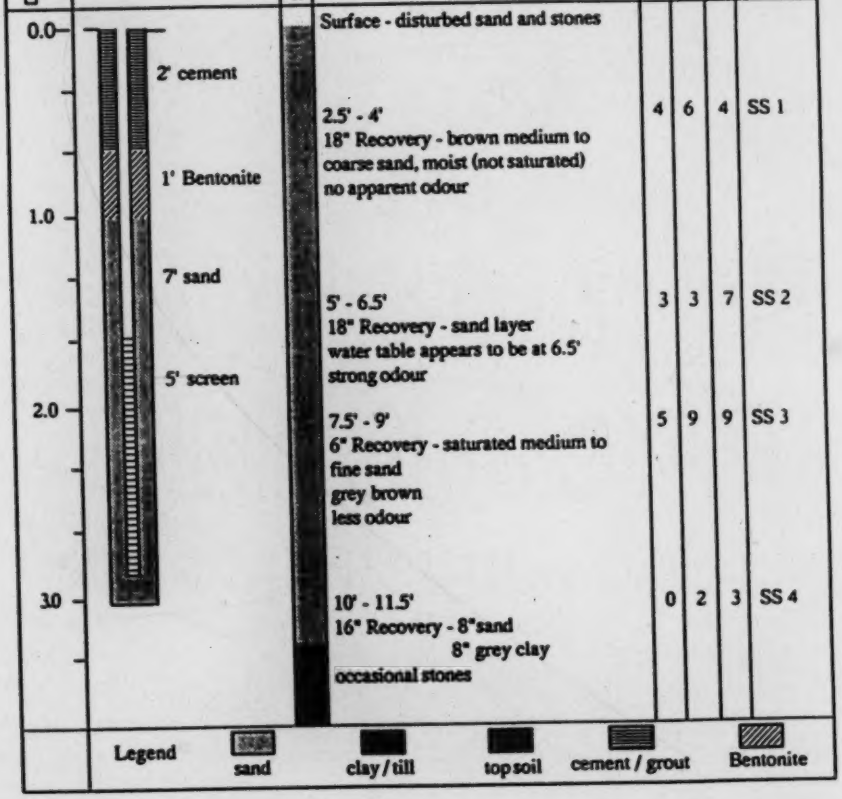
LOCATION 1 + 00W 1 + 00S

SHEET 1 of 1

DATE DRILLED 21 Aug '91

LOGGED BY Rob Hillier

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 13

PROJECT CFB Cold Lake Environmental Study

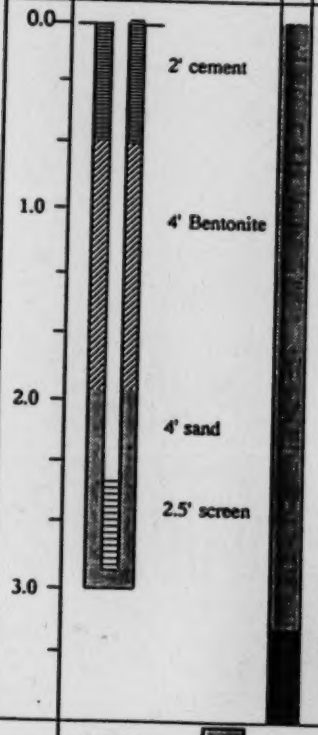
SHEET 1 of 1

LOCATION 1 + 50W 1 + 25S

DATE DRILLED 21 Aug '91

LOGGED BY R. Hillier

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

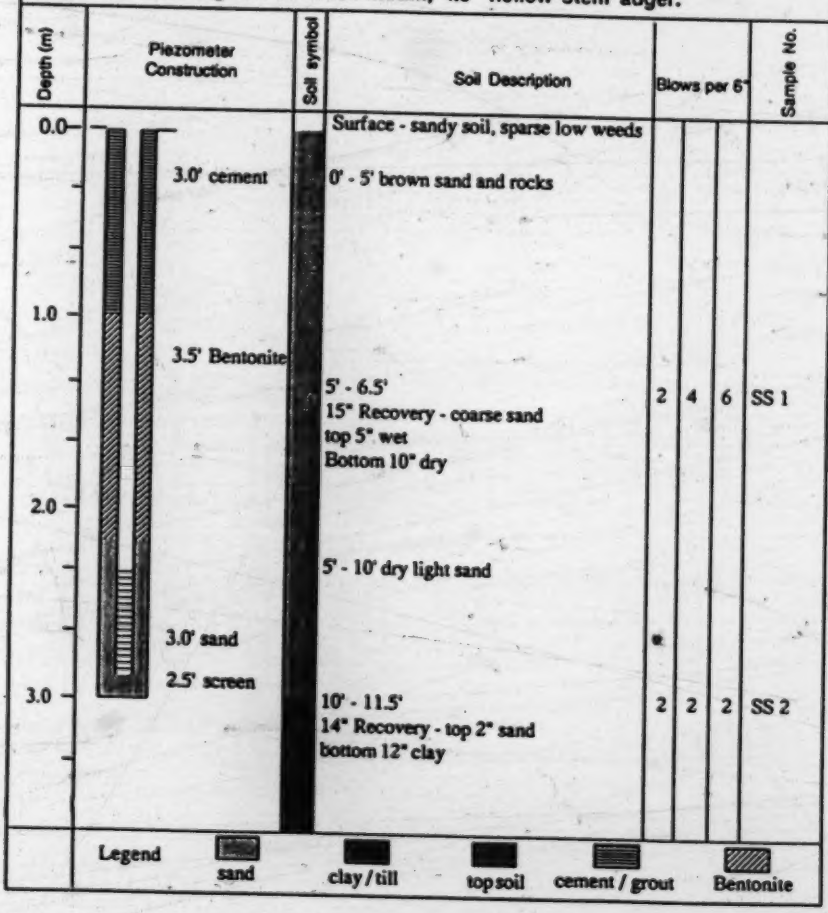


Soil Description	Blows per 6"			Sample No.
Surface - sandy soil occasional weeds 0' - 5' - dark brown sand, some stones				
4.5' - 6' 12" Recovery - sand medium to coarse grained wet at 6' no odour	5	6	9	SS 1
10' - 11.5' 13" Recovery - wet coarse sand clay at 10.5' no odour	1	3	3	SS 2

Legend: sand; clay / till; topsoil; cement / grout; Bentonite

Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	14
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 50W 2 + 00S	DATE DRILLED 21 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group

BOREHOLE NO. 15

SOIL LOG SHEET

PROJECT CFB Cold Lake Environmental Study

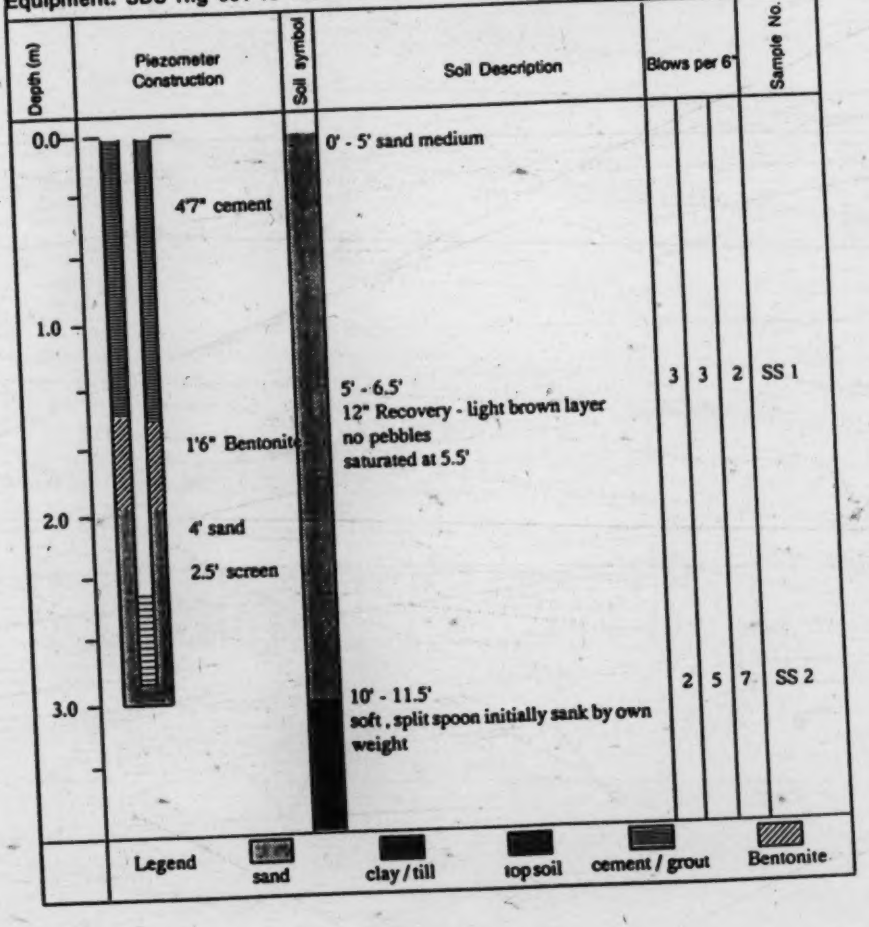
SHEET 1 of 1

DATE DRILLED 21 Aug '91

LOCATION 1 + 00W 2 + 00S

LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO. 16A
SOIL LOG SHEET	
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 3
LOCATION 0 + 70W 1 + 50N	DATE DRILLED 22 Aug '91
	LOGGED BY R. Hillier

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

Depth (m)	Piezometer Construction	Soil symbol	Soil Description	Blows per 6"			Sample No.
0.0	top 2' cement		Surface - long grass, peat soil 0' - 1.5' 1" Recovery - organic peat very soft, moist (not saturated) no odour	0	0	1	SS 1
1.0	2' to 28' grout		2.5' - 4' 8" Recovery - top 2" peat, then sand	3	4	3	SS 2
			5' - 6.5' 3" Recovery - 2" sand 1" clay	0	0	0	SS 3
2.0			7.5' - 9' 14" Recovery - clay, dark grey, very cohesive no fracturing evident	0	3	6	SS 4
3.0			11' - 12.5' 18" Recovery - very tight clay till occassional pebbles ~ 5% silt ~ 5 - 10% 13' auger passed by large cobble or boulder	4	10	20	SS 5
4.0							

Legend: sand; clay / till; top soil; cement / grout; Bentonite

Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 16A

PROJECT CFB Cold Lake Environmental Study

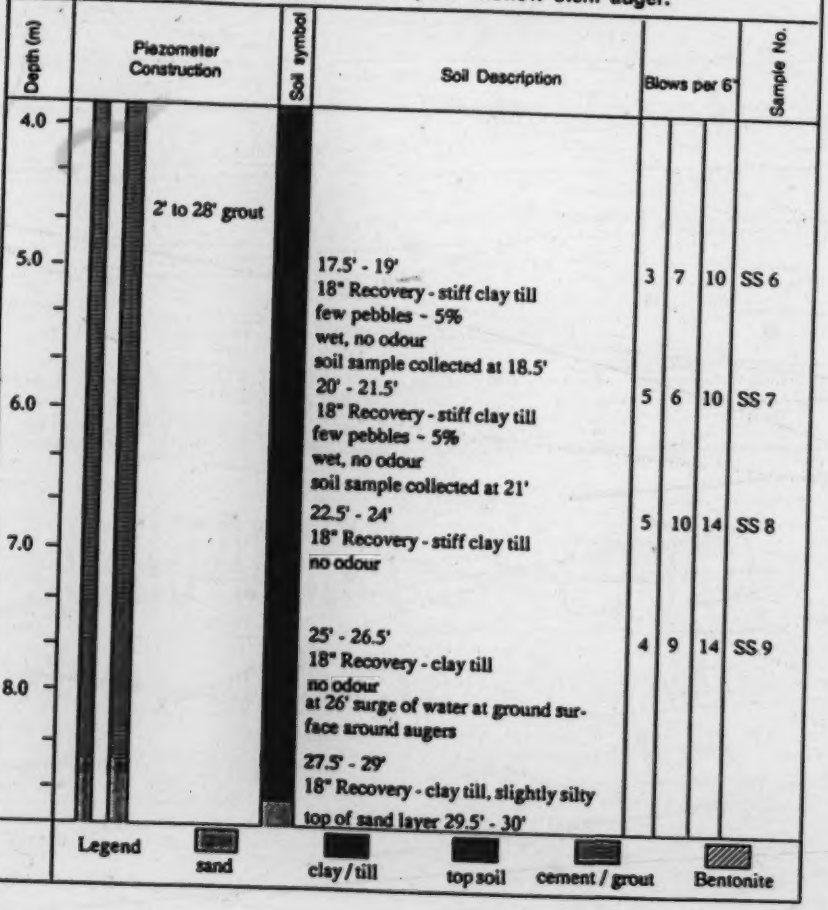
SHEET 2 of 3

LOCATION 0 + 70W 1 + 50N

DATE DRILLED 22 Aug '91

LOGGED BY R. Hillier

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	16A
PROJECT CFB Cold Lake Environmental Study	SHEET 3 of 3
LOCATION 0 + 70W 1 + 50N	DATE DRILLED 22 Aug '91
	LOGGED BY R. Hillier

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

Depth (m)	Piezometer Construction	Soil symbol	Soil Description	Blows per 6"	Sample No.
10.0	sand		30' - 31.5' 12" Recovery - sand, medium grain no apparent odour		
			32.5' - 34' 12" Recovery - 32.5' - 33.75' - very coarse sand & stones 33.75' - 34' - fine sand, silt at very end of spoon	32 27 10	SS 12
11.0	2.5' screen				
	35'		35.5' - 36.5' 18" Recovery - 35' - 35' 2" - sand, no odour 35' 2" - 36.5' - clay till, hand tight some stones, dark grey colour	4 12 21	SS 13

Legend: sand; clay / till; topsoil; cement / grout; Bentonite

Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 16B

PROJECT CFB Cold Lake Environmental Study

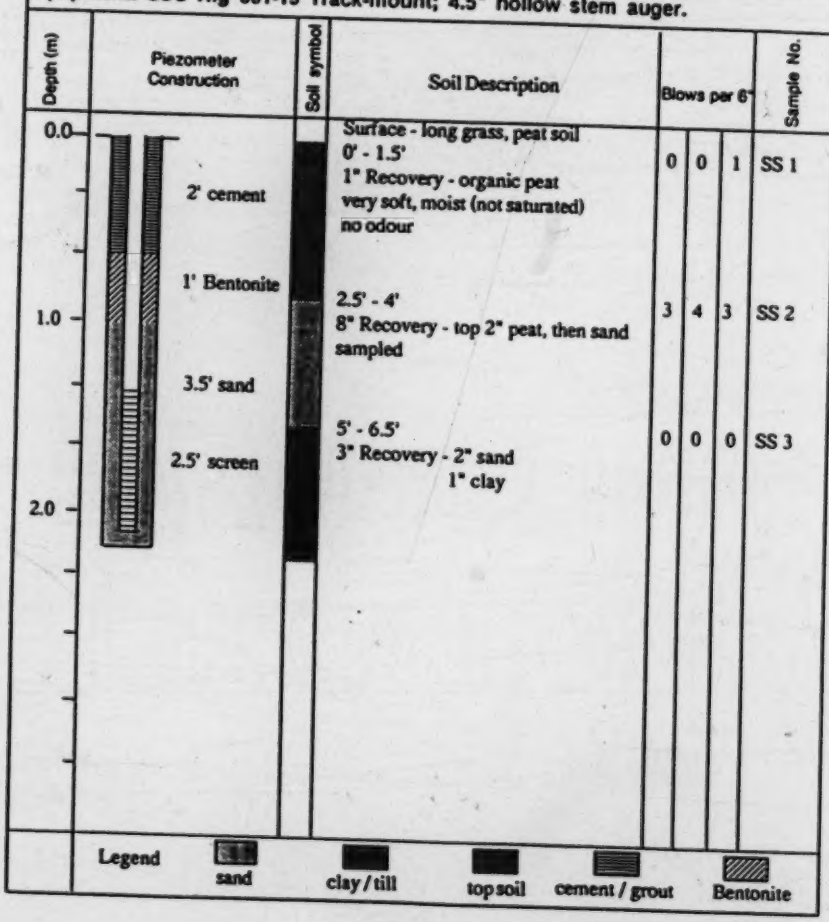
SHEET 1 of 1

LOCATION 0 + 70W 1 + 50N

DATE DRILLED 22 Aug '91

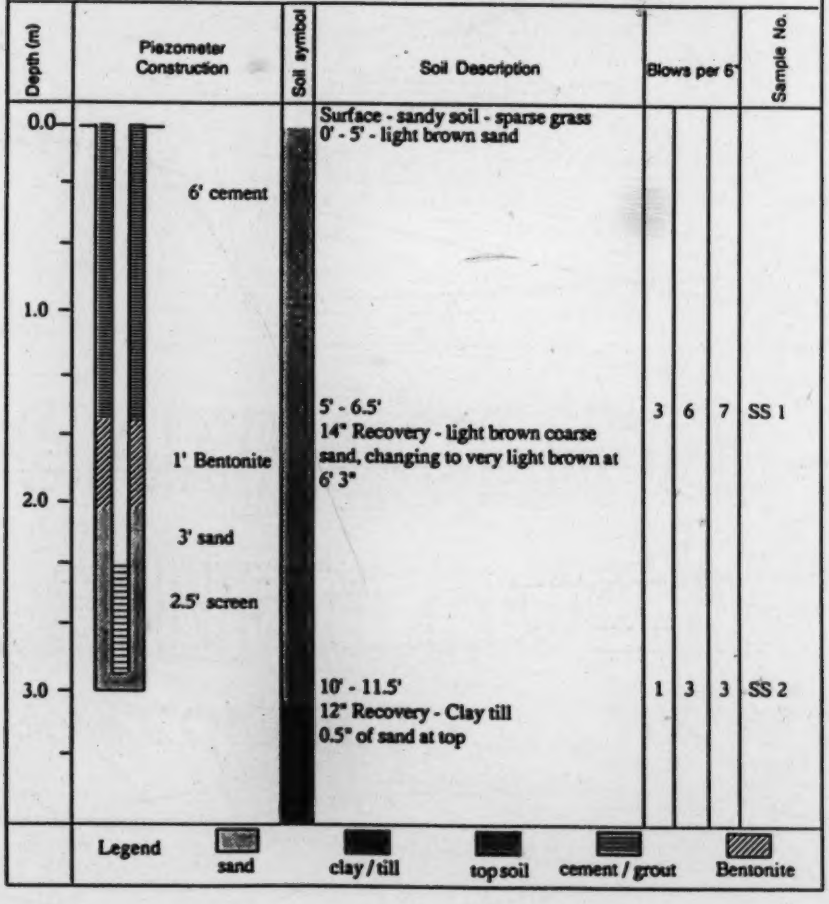
LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



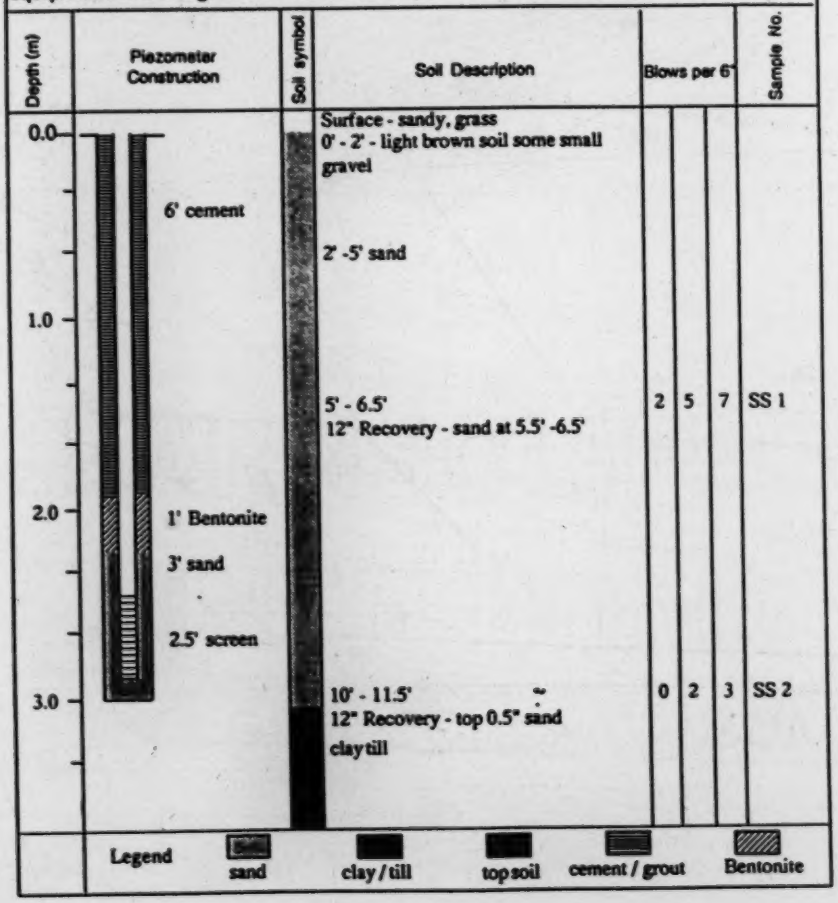
Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	17
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 1 + 00W 1 + 50S	DATE DRILLED 22 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



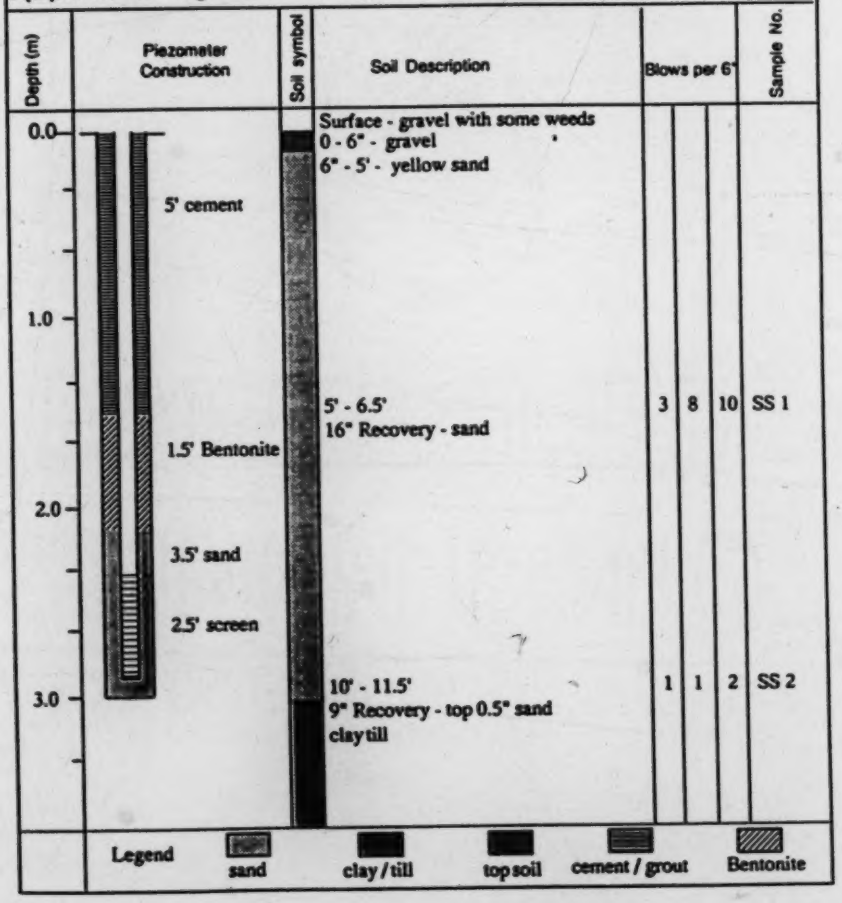
Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO. 18
SOIL LOG SHEET	
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 20E 0 + 40S	DATE DRILLED 22 Aug '91
	LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



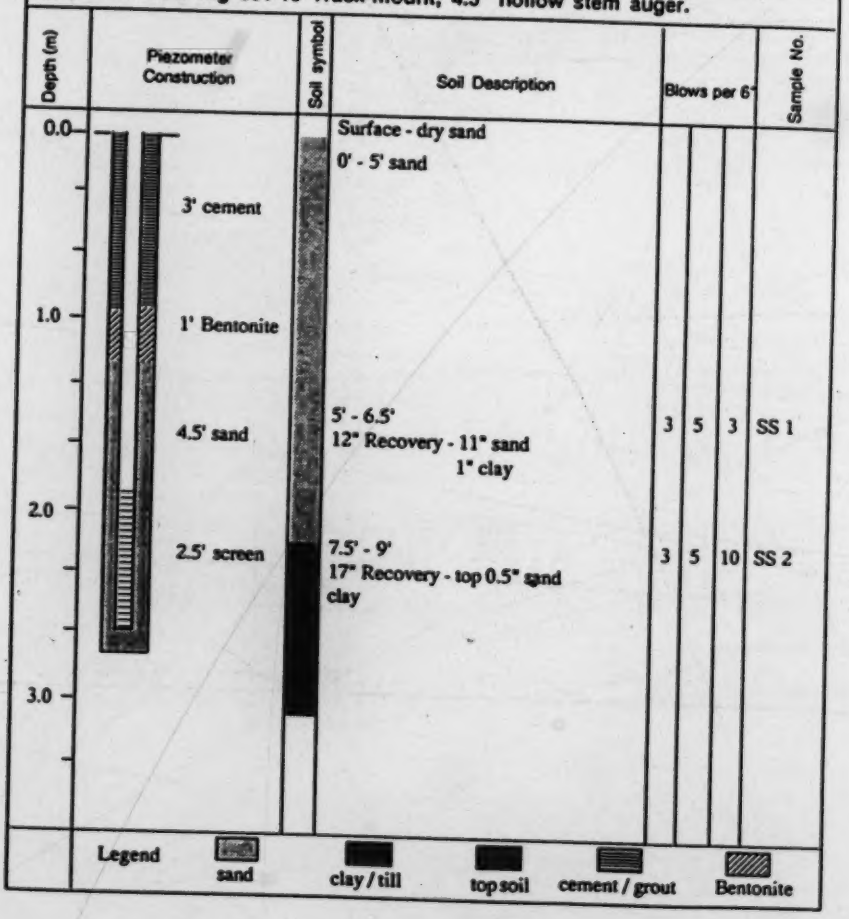
Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	19
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
	DATE DRILLED 23 Aug '91
LOCATION 0 + 45E 1 + 00S	LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	20
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 75E 2 + 00S	DATE DRILLED 23 Aug '91
	LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 21

PROJECT CFB Cold Lake Environmental Study

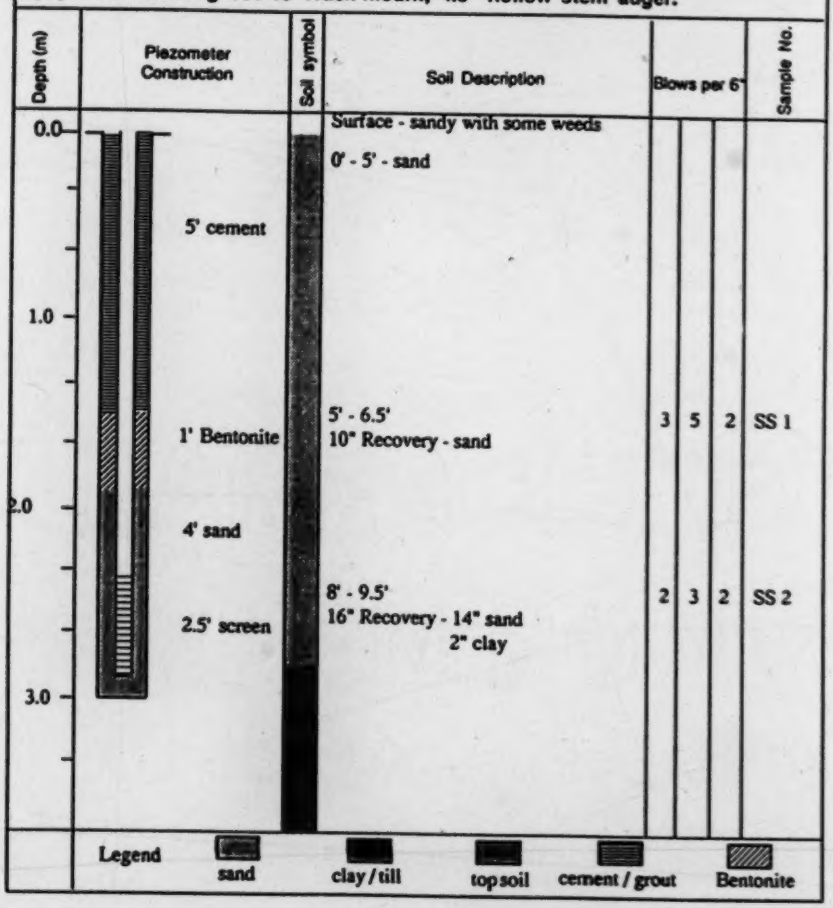
LOCATION 0 + 25E 2 + 00S

SHEET 1 of 1

DATE DRILLED 23 Aug '91

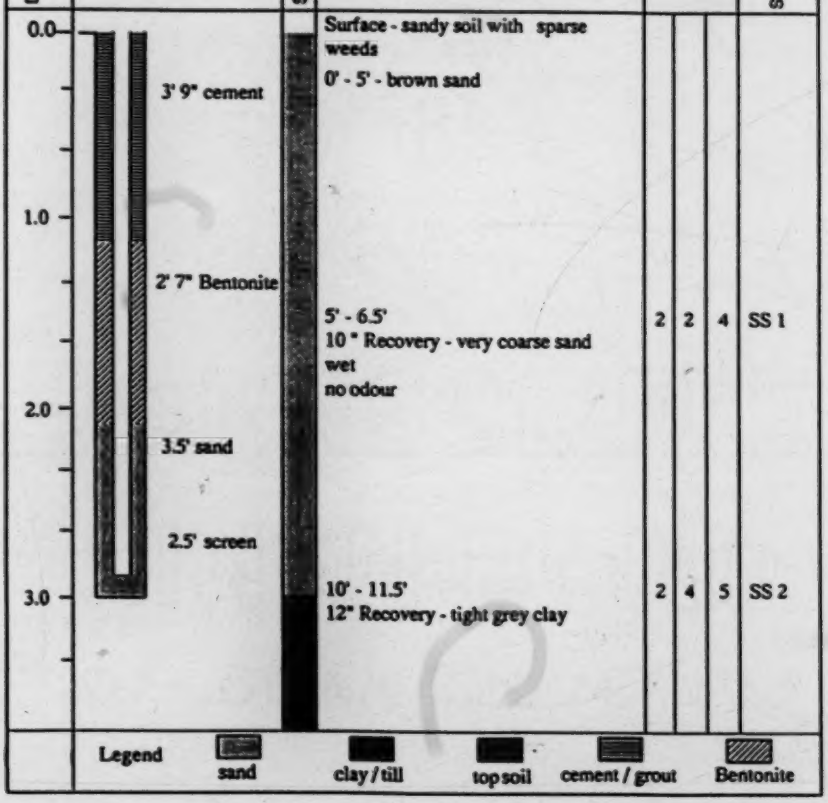
LOGGED BY J. Poland

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



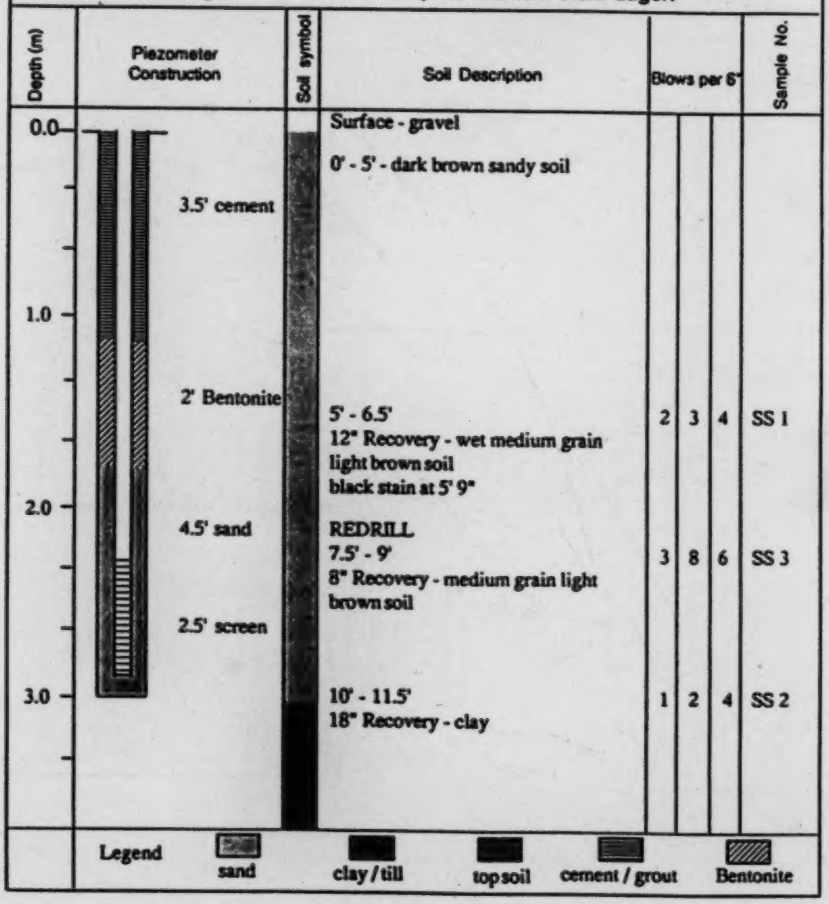
Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	22
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 1 + 00E 1 + 80S	DATE DRILLED 23 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	23
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 50 W 0 + 80S	DATE DRILLED 23 Aug '91
	LOGGED BY S. Grundy

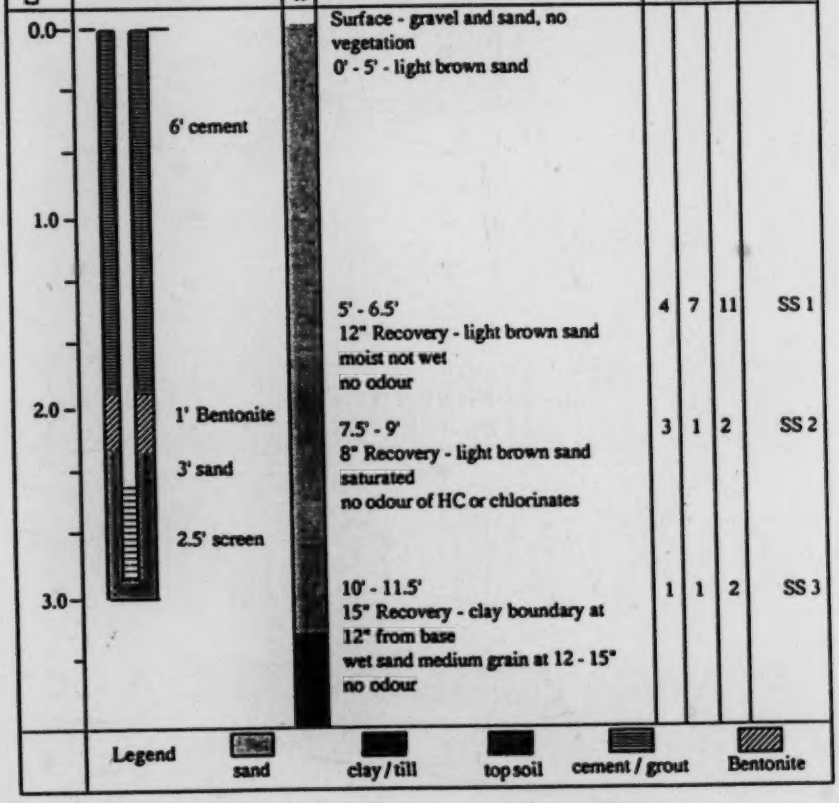
Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO. 24
SOIL LOG SHEET	

PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
	DATE DRILLED 24 Aug '91
LOCATION 0 + 12W 1 + 35S	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	25

PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 00E 2 + 00N	DATE DRILLED 24 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

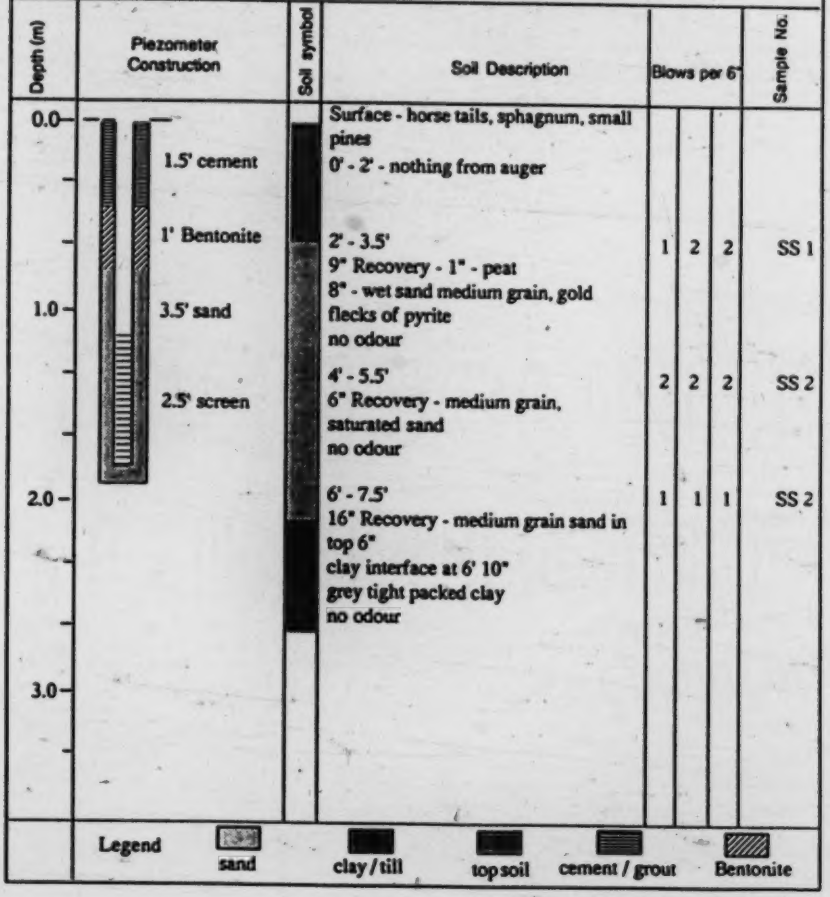
Depth (m)	Piezometer Construction	Soil symbol	Soil Description	Blows per 6"	Sample No.
0.0	3" cement 1' Bentonite 2' 3" sand 2' screen		Surface - sphagnum mat, small pines 0' 2.5' - sphagnum bed than black saturated peat		
1.0			2.5' - 4' 1" Recovery - clay clay boundary at 2.5'	0 0 1	SS 1
2.0					
3.0					

Legend: sand; clay / till; topsoil; cement / grout; Bentonite

Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	26

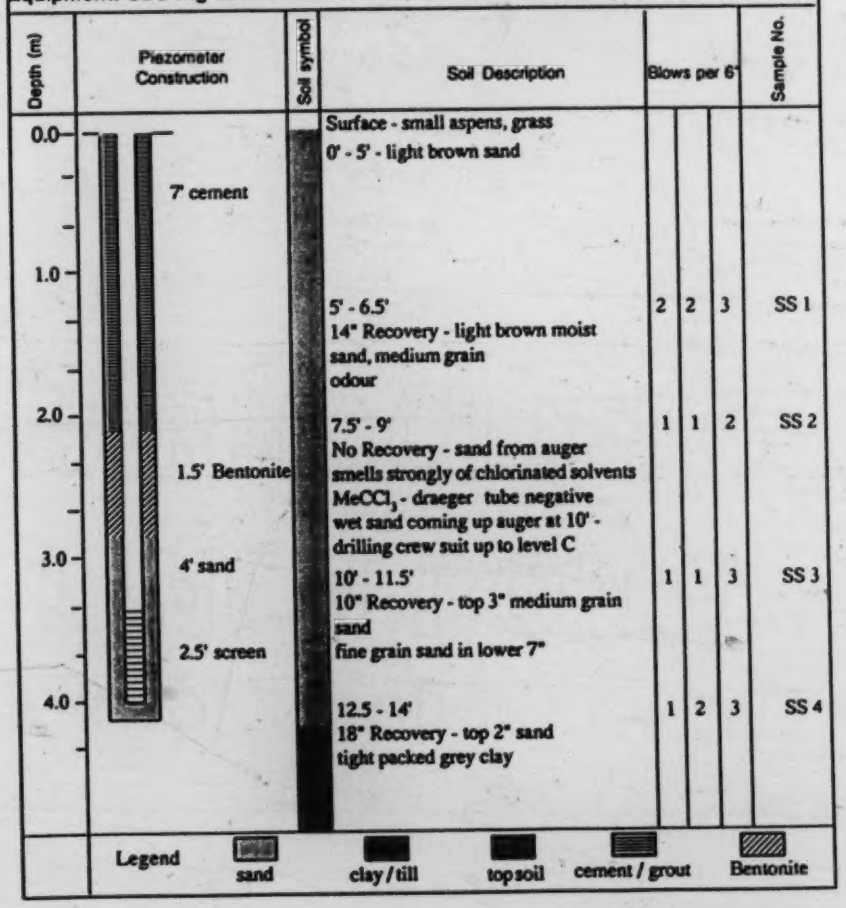
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 1 + 15W 0 + 75N	DATE DRILLED 24 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO. 27
SOIL LOG SHEET	
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
	DATE DRILLED 24 Aug '91
LOCATION 0 + 75W 0 + 15N	LOGGED BY S. Grundy

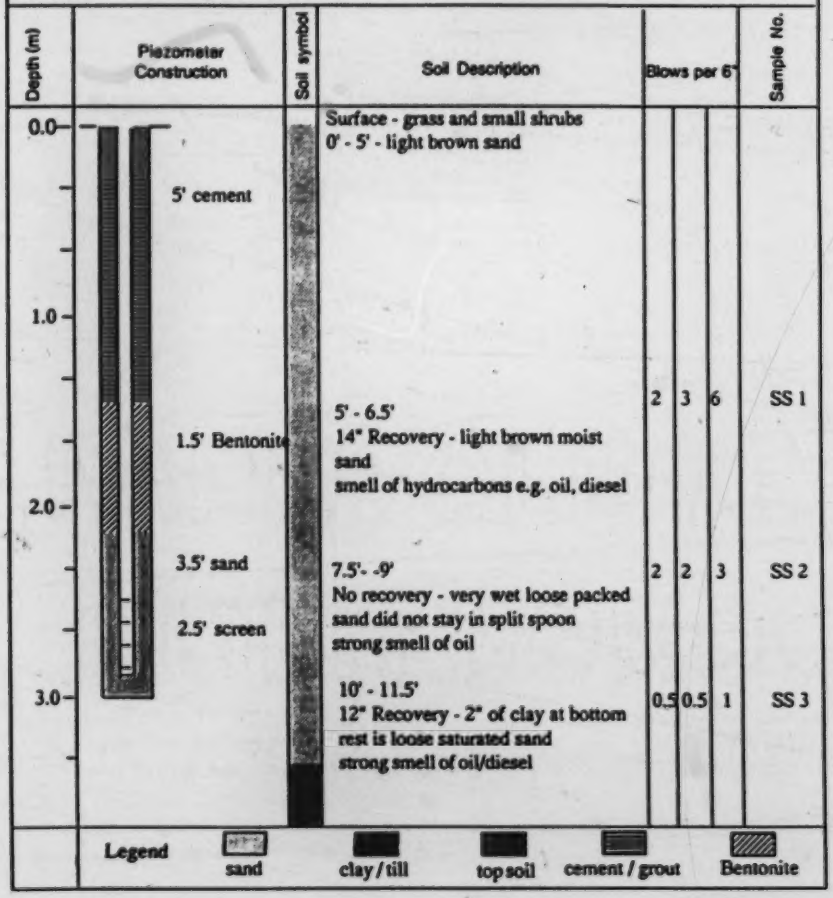
Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	28

PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
	DATE DRILLED 24 Aug '91
LOCATION 0 + 10W 0 + 35N	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group

SOIL LOG SHEET

BOREHOLE NO. 29

PROJECT CFB Cold Lake Environmental Study

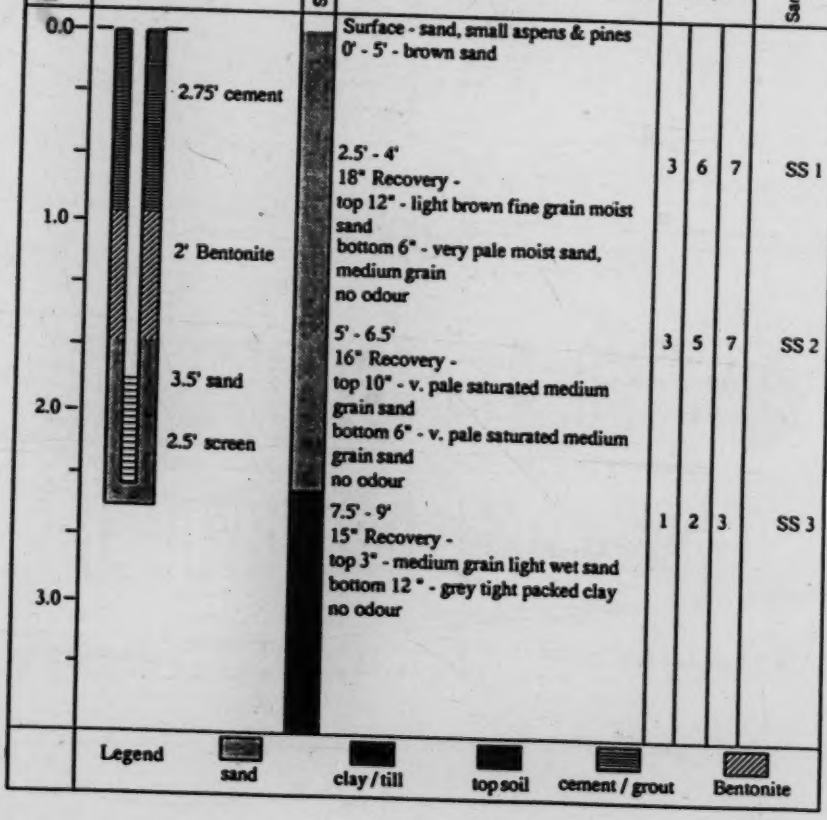
LOCATION 0 + 75E 1 + 00S

SHEET 1 of 1

DATE DRILLED 25 Aug '91

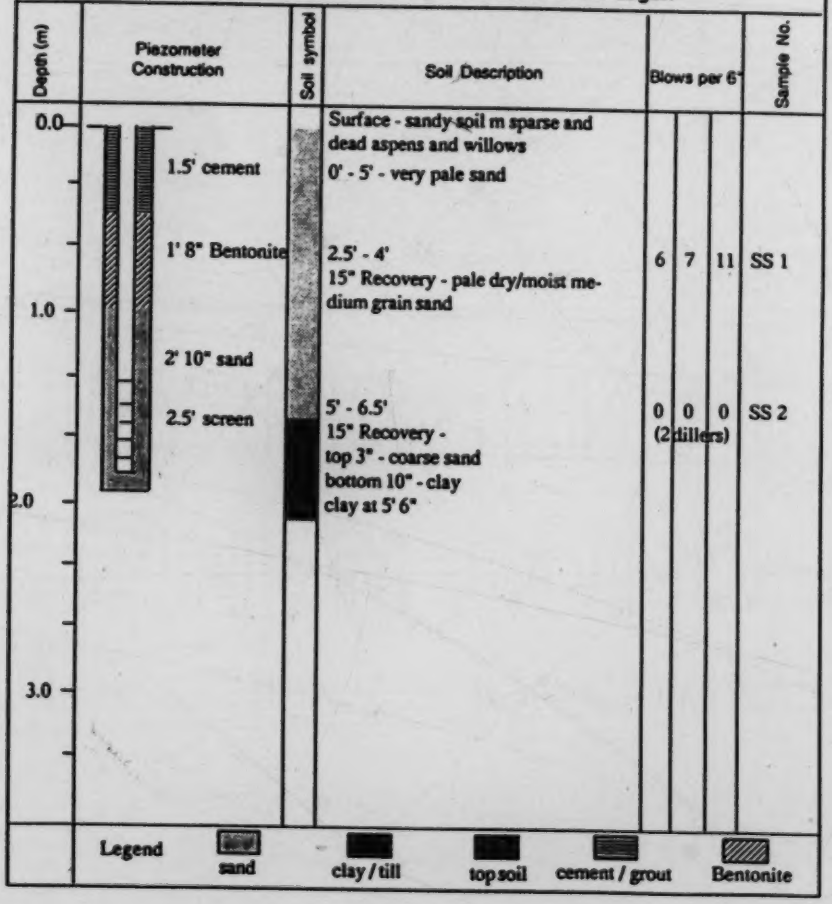
LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group	BOREHOLE NO.
SOIL LOG SHEET	36
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 87m from road junction along abandoned road	DATE DRILLED 25 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.



Royal Roads Military College, Environmental Sciences Group				HOLE NO.
SOIL LOG SHEET				30
PROJECT CFB Cold Lake Environmental Study			SHEET 1 of 1	
LOCATION 0 + 75W 1 + 75S			DATE DRILLED 25 Aug '91	
			LOGGED BY S. Grundy	
Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.				

	Soil Description	Blows per 6"			Sample No.
	Surface - sandy soil, sparse grass 0' - 5' - brown sandy soil 0' - 1.5' - move 1' forward 7" Recovery - stone in keeper no odour				
	2.5' - 4' 16" Recovery - top 14" - black oily sand/soil and some roots (probably back fill) bottom 2" - brown sand	2	3	4	SS 1
	5' - 6.5' 13" Recovery - light medium grain sand, moist odour	3	6	7	SS 2
	7.5' - 9' 15" Recovery - top 3" - coarse grey sand bottom 12" - tight packed grey clay sample at sand/clay interface	0	1	2	SS 3

Royal Roads Military College, Environmental Sciences Group	HOLE NO. 31
SOIL LOG SHEET	
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
	DATE DRILLED 25 Aug '91
LOCATION 0 + 50W 1 + 75S	LOGGED BY S. Grundy
Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.	

	Soil Description	Blows per 6"			Sample No.
	Surface - sandy soil/fill, very sparse vegetation				
	0'- 1.5' 15" Recovery - dark brown rooted soil, some charcoal and sand light brown soil at tip of split spoon no odour	20	total		SS 1
	2.5' - 4' 14"Recovery - light brown medium grain moist sand no odour	4	8	10	SS 2
	5' - 6.5' 14" Recovery - light brown medium grain moist sand no odour	4	6	7	SS 3
	7.5' - 9' 10" Recovery - 8" - coarse sand 2" - clay sample at interface clay at 8'	1	2	2	SS 4

Royal Roads Military College, Environmental Sciences Group		HOLE NO.
SOIL LOG SHEET		32
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1	
LOCATION 1 + 00W 1 + 75S	DATE DRILLED 25 Aug '91	
	LOGGED BY S. Grundy	

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

	Soil Description	Blows per 6"			Sample No.
	Surface - grey soil, long grass				
	0' - 5' - brown sand 0' - 1.5' 7" Recovery - brown dry soil, some stones no odour	33	total		SS 1
	2.5' - 4' 13" Recovery - brown medium grain moist sand no odour	1	2	6	SS 2
	5' - 6.5' 12" Recovery - saturated top 9" - medium grain sand bottom 3" - coarse sand no odour	3	6	11	SS 3
	7.5' - 9' 18" Recovery - clay between 6.5'-7.5' top 17" - clay bottom 1" - sand no odour	1	1	1	SS 4

Royal Roads Military College, Environmental Sciences Group	HOLE NO.
SOIL LOG SHEET	33

PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 + 75W 2 + 00S	DATE DRILLED 25 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

	Soil Description	Blows per 6"	Sample No.
	Surface - light sandy soil, sparse weeds 0' - 1' 8" Recovery - dry sandy soil/fill no odour hit rock - move north 1m Attempt #2 - hit rock - move back (2m south) Attempt #3 - rocks again at 2' - move 5 m south Attempt #4 - rocks at 2'		

Royal Roads Military College, Environmental Sciences Group	HOLE NO.
SOIL LOG SHEET	34
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1
LOCATION 0 +87.5W 1 + 75S	DATE DRILLED 25 Aug '91
	LOGGED BY S. Grundy

Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.

Soil Description	Blows per 6"			Sample No.
Surface - light sandy soil, sparse weeds and grass				
0' - 1.5'	total 41			SS 1
18" Recovery - brown sandy soil and pink granite rocks				
no odour	4	8	12	SS 2
2.5' - 4'				
12" Recovery - brown moist sand				
darker sand in lower 2" of sample				
sample taken at interface				
possible very slight odour	3	6	7	SS 3
5' - 6.5'				
12" Recovery -				
top 8" - wet medium grain light sand				
bottom 3" - coarse wet sand				
oil and grease odour	0	1	2	SS 4
7.5' - 9'				
16" Recovery -				
top 2" - sand				
Bottom 14" - clay				
sample at interface				
clay at 8'				

Royal Roads Military College, Environmental Sciences Group		HOLE NO.
SOIL LOG SHEET		35
PROJECT CFB Cold Lake Environmental Study	SHEET 1 of 1	
LOCATION 1 + 75E 3 + 25S	DATE DRILLED 25 Aug '91	
Equipment: SDS Rig 601-19 Track-mount; 4.5" hollow stem auger.	LOGGED BY S. Grundy	

	Soil Description	Blows per 6"			Sample No.
	0' - 5' - brown medium grain sand				
	2.5' - 4' 15" Recovery - light brown moist medium grain sand no odour	3	7	9	SS 1
	5' - 6.5 clay at 5' no water	1	2	3	SS 2

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada	BOREHOLE NO.: BH 201
	DRILL: Mobile Augers	JOB NO.: 010-A003-01
		ELEVATION: 538.46 m

SAMPLE TYPE: SHELBY · DISTURBED · SPLIT SPOON · NO RECOVERY · A CASING · CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	STANDARD PENETRATION COUNT (DYNAMIC CONE COUNT) 10 20 30 40	WELL
0		Surface - 4 " - grass, organics				
1		12 " Recovery - sand, orange brown, fine to medium, compact		2.5 ' - 4 '		
	5	12 " Recovery - 6 " - sand, orange brown, fine to medium, compact 6 " - sand, orange brown, coarse, compact		5 ' - 6.5 '		
2		0 " Recovery		7.5 ' - 9 '		
3	10	18 " Recovery - 2 " - sand , brown, coarse, loose, wet 16 " - clay (till) - silty, olive grey, medium		10 ' - 11.5 '		
4		12 " Recovery - clay (till) - silty, grey, medium to stiff with pebbles		12.5 ' - 14 '		
	15	18 " Recovery - clay (till) - silty, grey, very stiff with pebbles		15 ' - 16.5 '		
5		EXPLORATION DEPTH (5.0 m) STANDPIPE INSTALLED TO 4.8 m				
6	20					
7						
	25					
8						
9	30					
10						
	33					

AH-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH	COMPLETION DEPTH: 5.0 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 1	PAGE: B1 of B13

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada DRILL: Mobile Augers	BOREHOLE NO.: BH 202 JOB NO.: 010-A003-01 ELEVATION: 538.38 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	◆STANDARD PENETRATION COUNT◆ ■ DYNAMIC CONE COUNT ■ 10 20 30 40	WELL
		Surface - 4 " - sand , brown, loose, moist, with organics				
1		15 " Recovery - 6 " - sand, greyish black, compact, organics 9 " - sand, brown, medium to fine, compact, moist, slight hydrocarbon odour		2.5 ' - 4 '		
	5	13 " Recovery - 6 " - sand, orange brown, coarse, loose to compact		5 ' - 6.5 '		
2		2 " Recovery - sand, orange brown, coarse, loose		7.5 ' - 9 '		
3	10	18 " Recovery - 12 " - sand, olive brown, very loose coarse 6 " - clay (till) - silty, olive, soft, wet		10 ' - 11.5 '		
4		12 " Recovery - 12 " - clay (till) - silty, olive, medium with pebbles		12.5 ' - 14		
		EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.2 m				
5	15					
6	20					
7						
8	25					
9	30					
10						
	35					

AN-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH REVIEWED BY: PM FIGURE NO.: 2	COMPLETION DEPTH 4.3 m DATE: 97-07-31 PAGE: B2 of B15

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada DRILL: Mobile Augers	BOREHOLE NO.: BH 203 JOB NO.: 010-A003-01 ELEVATION: 534.96 m

SAMPLE TYPE: ■ SHELBY ■ DISTURBED ■ SPLIT SPOON ■ NO RECOVERY ■ A CASING ■ CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	STANDARD PENETRATION COUNT / DYNAMIC CONE COUNT (10 20 30 40)	WELL
		Surface - 5" - vegetation, wood pieces, organics				
1		3 " Recovery - 2 " - wood pieces 1 " - sand, mottle orange brown, coarse, very loose, wet	■	2.5 ' - 4 '		
	5	12 " Recovery - 4 " - sand, mottle olive brown, coarse, loose, wet 8 " - clay (till) - sandy, grey, stiff, moist with pebbles, coal pieces	■	5 ' - 6.5 '		
2		18 " Recovery - clay (till) - sandy, grey, stiff, moist with pebbles, coal pieces	■	7.5 ' - 9 '		
3	10	17 " Recovery - clay (till) - sandy, grey, very stiff, moist with 1/2 inch pebbles	■	10 ' - 11.5 '		
4		EXPLORATION DEPTH (3.5 m) STANDPIPE INSTALLED TO 3.3 m				
	15					
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AH-CED ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DE REVIEWED BY: PM FIGURE NO.: 3	COMPLETION DEPTH: 3.5 m DATE: 97-07-31 PAGE: B3 of B15

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada	BOREHOLE NO.: BH 204
	DRILL: Mobile Augers	JOB NO.: 010-A003-01
		ELEVATION: 535.58 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	• STANDARD PENETRATION COUNT • # DYNAMIC CONE COUNT # (10 20 30 40)	WELL
		Surface - 3 " - vegetation, organics				
1		18 " Recovery - sand, orange brown, medium, compact, wet		2.5 ' - 4 '		
	5	9 " Recovery - sand, mottle grey brown, medium to coarse, loose to compact with moderate hydrocarbon odour		5 ' - 6.5 '		
2		18 " Recovery - 4 " - sand, mottle grey brown, medium to coarse, loose, with moderate hydrocarbon odour 14 " clay (till) - sandy, olive grey, medium to stiff, moist with strong odour		7.5 ' - 9 '		
3	10	17 " Recovery - clay (till) - sandy, grey, very stiff, moist with pebbles		10 ' - 11.5 '		
4		18 " Recovery - clay (till) - sandy, grey, stiff to very stiff, moist with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 3.8 m				
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AH-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH	COMPLETION DEPTH: 4.3 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 4	PAGE: B4 of B15

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada DRILL: Mobile Augers	BOREHOLE NO.: BH 205 JOB NO.: 010-A003-01 ELEVATION: 535.53 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	STANDARD PENETRATION COUNT / DYNAMIC CONE COUNT (10 20 30 40)	WELL
		Surface - 3 " - wood pieces, organics				
1		6 " Recovery - mud, grey, medium to coarse, compact, wet		2.5 ' - 4 '		
	5	14 " Recovery - mud, grey, medium to coarse, loose, wet with black diesel/ oil stains, strong hydrocarbon odour		5 ' - 6.5 '		
2		18 " Recovery - 6 " - mud, grey, medium to coarse, loose, wet with moderate hydrocarbon odour 12 " clay (till) - silty, grey, medium, moist		7.5 ' - 9 '		
3	10	2 " Recovery - clay (till) - silty, grey, medium, moist		10 ' - 11.5 '		
4		16 " Recovery - clay (till) - silty, grey, very stiff with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.1 m				
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AN-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH REVIEWED BY: PH FIGURE NO.: 5	COMPLETION DEPTH 4.3 m DATE 97-07-31 PAGE B3 of B13

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Dufferin Construction Canada	BOREHOLE NO.: BH 206
	DRILL: Mobile Augers	JOB NO.: 010-A003-01
		ELEVATION: 535.99 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	• STANDARD PENETRATION COUNT • ▲ DYNAMIC CONE COUNT ▲ 10 20 30 40	WELL
		Surface - 3 " - organics				
1		13 " Recovery - 2 " - organics 11 " - mud, orange brown (7 " y olive brown (4 "), medium to coarse, compact, wet with moderate hydrocarbon odour, stain bands		2.5 ' - 4 '		
	5	6 " Recovery - mud, mottle grey brown, fine, loose, wet with moderate hydrocarbon odour		5 ' - 6.5 '		
2						
		18 " Recovery - 6 " - mud, grey, medium to coarse loose, wet 12 " - clay (till) - silty, grey, medium with pebbles		7.5 ' - 9 '		
3	10	16 " Recovery - clay (till) - silty, grey, stiff to very stiff with pebbles		10 ' - 11.5 '		
4		18 " Recovery - clay (till) - silty, grey, stiff, with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.3 m				
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AM-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH	COMPLETION DEPTH 4.3 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 6	PAGE: B6 of B13

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada DRILL: Mobile Augers	BOREHOLE NO.: BH 207 JOB NO.: 010-A003-01 ELEVATION: 536.52 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	STANDARD PENETRATION COUNT (DYNAMIC CONE COUNT) 10 20 30 40	WELL
		Surface - 4 " - vegetation, organics				
1		13 " Recovery - 3 " - organics 10 " - sand, brown, coarse, compact, with 1/2 cm bands of oil stains, slight hydrocarbon odour		2.5 ' - 4 '		
	5	4 " Recovery - sand, olive brown, coarse, loose, wet		5 ' - 6.5 '		
2		18 " Recovery - 3 " - sand, olive brown, coarse, compact, wet 15 " - clay (till) - silty, grey, stiff, moist to wet with pebbles		7.5 ' - 9 '		
3	10	16 " Recovery - clay (till) - silty, grey, stiff, moist with pebbles		10 ' - 11.5 '		
4		18 " Recovery - clay (till) - silty, grey, very stiff, moist with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.1 m				
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AH-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH REVIEWED BY: PM FIGURE NO.: 7	COMPLETION DEPTH 4.3 m DATE: 97-07-31 PAGE: B7 of B13

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada DRILL: Mobile Augers	BOREHOLE NO.: BH 208 JOB NO.: 010-A003-01 ELEVATION: 536.61 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	STANDARD PENETRATION COUNT + DYNAMIC CONE COUNT # (10 20 30 40)	WELL
		Surface - 4 " - vegetation, organics				
1		3 " Recovery - 2 " - wood pieces 1 " - sand, silty, brown, medium to fine, loose, wet		2.5 ' - 4 '		
	5	18 " Recovery - 16 " - sand, brown, medium to coarse, very loose, wet 2 " - clay (till) - silty, grey, very soft to soft, stiff, moist to wet		5 ' - 6.5 '		
2		11 " Recovery - clay (till) - silty, grey, medium, moist with pebbles		7.5 ' - 9 '		
3	10	13 " Recovery - clay (till) - silty, grey, stiff moist with pebbles		10 ' - 11.5 '		
4		18 " Recovery - clay (till) - silty, grey, very stiff, moist with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.1 m				
5						
6	20					
7						
8	25					
9	30					
10						
	33					

AN-GED ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DE REVIEWED BY: FM FIGURE NO.: 8	COMPLETION DEPTH 4.3 m DATE: 97-07-31 PAGE: B8 of B15

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada	BOREHOLE NO.: BH 209
	DRILL: Mobile Auger	JOB NO.: 010-A003-01
		ELEVATION: 536.35 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	• STANDARD PENETRATION COUNT • / ▫ DYNAMIC CONE COUNT ▫ 10 20 30 40	WELL
		Surface - 2 " - organics				
1		16 " Recovery - 2 " - organics 14 " - sand, silty, orange brown, fine loose, moist		2.5' - 4'		
	5	18 " Recovery - 6 " - sand, silty, orange brown, fine, very loose to loose, moist 12 " - clay (till) - sandy, grey, soft to medium with varve sand layers		5' - 6.5'		
2						
		18 " Recovery - clay (till) - silty, grey, very stiff with pebbles		7.5' - 9'		
3	10					
		EXPLORATION DEPTH (3.2 m) STANDPIPE INSTALLED TO 3.2 m				
4						
	15					
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

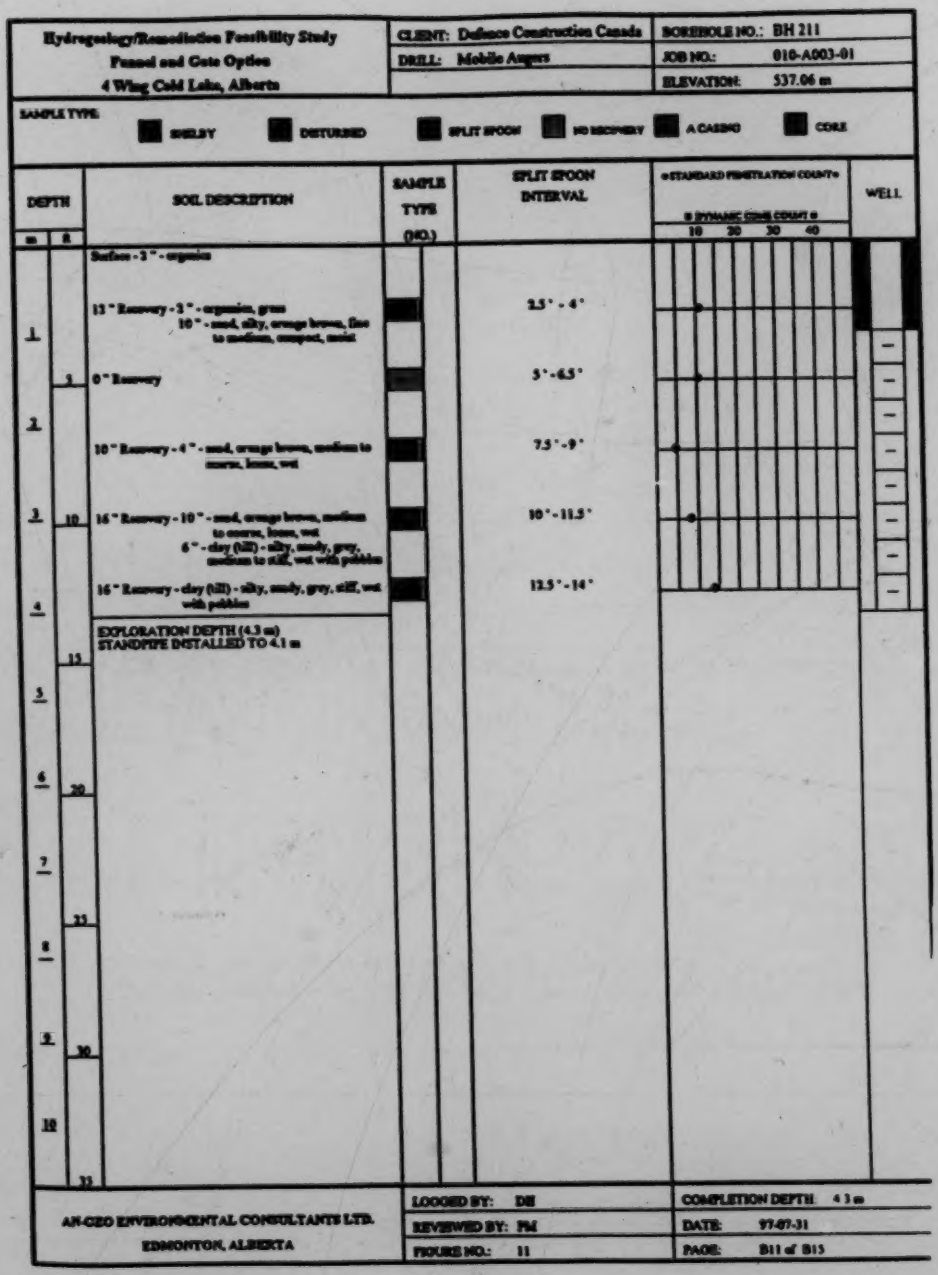
AN-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DH	COMPLETION DEPTH: 3.2 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 9	PAGE: 89 of 113

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada	BOREHOLE NO.: BH 210
	DRILL: Mobile Augers	JOB NO.: 010-A003-01
		ELEVATION: 535.93 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	● STANDARD PENETRATION COUNT ● / ○ DYNAMIC CONE COUNT ○ (10 20 30 40)	WELL
0		Surface - 3 " - vegetation, organics				
1		13 " Recovery - 3 " - organics, grass 10 " - sand, grey, fine to medium, compact, wet with strong hydrocarbon odour		3.5 ' - 4 '		
	5	18 " Recovery - 12 " - sand, grey, medium to coarse, very loose to loose, wet with strong hydrocarbon odour 6 " - clay (till) - silty, olive brown, soft to medium, moist with pebbles		5 ' - 6.5 '		
2		7 " Recovery - clay (till) - silty, grey, stiff, moist with pebbles		7.5 ' - 9 '		
3	10	6 " Recovery - clay (till) - silty, grey, stiff with pebbles		10 ' - 11.5 '		
4		13 " Recovery - clay (till) - silty, very stiff with pebbles		12.5 ' - 14 '		
	15	EXPLORATON DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.1 m				
5						
6	20					
7						
	23					
8						
9	30					
10						
	33					

AMEC ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DE	COMPLETION DEPTH 4.3 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 10	PAGE: B10 of B13

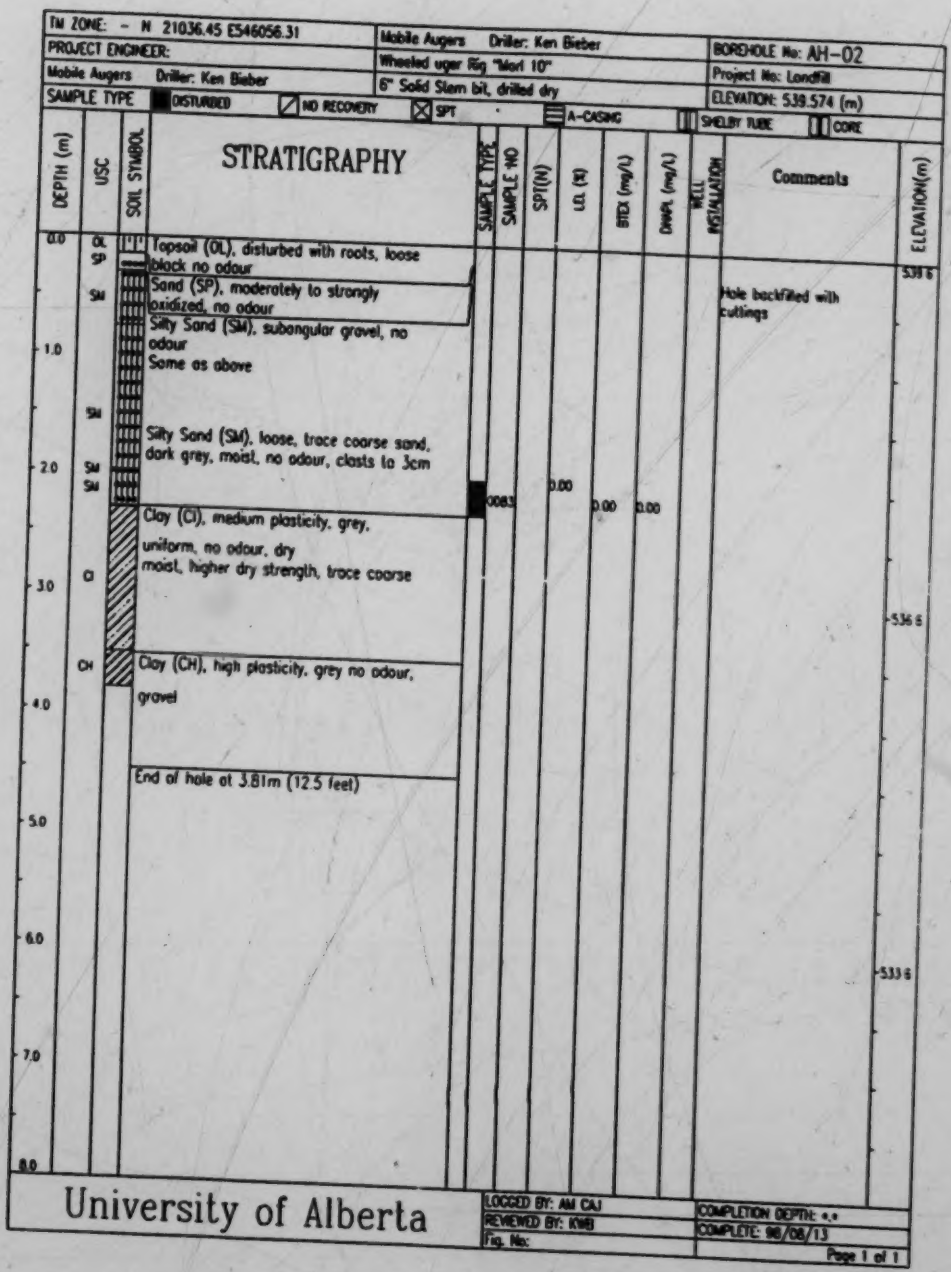

Hydrogeology/Remediation Feasibility Study
Funnel and Gate Option
4 Wing Cold Lake, Alberta
CLIENT: Defence Construction Canada
DRILL: Mobile Augers
BOREHOLE NO.: BH 211
JOB NO.: 010-A003-01
ELEVATION: 537.06 m
SAMPLE TYPE
SHELBY
DISTURBED
SPLIT SPOON
NO RECOVERY
A CASING
CORE
DEPTH
m
ft
SOIL DESCRIPTION
SAMPLE TYPE (NO.)
SPLIT SPOON INTERVAL
STANDARD PENETRATION COUNT
DYNAMIC CONE COUNT
10
20
30
40
WELL
Surface - 3 " - organics
13 " Recovery - 3 " - organics, grass
10 " - sand, silty, orange brown, fine to medium, compact, moist
2.5' - 4'
0 " Recovery
5' - 6.5'
10 " Recovery - 4 " - sand, orange brown, medium to coarse, loose, wet
7.5' - 9'
16 " Recovery - 10 " - sand, orange brown, medium to coarse, loose, wet
6 " - clay (till) - silty, sandy, grey, medium to stiff, wet with pebbles
10' - 11.5'
16 " Recovery - clay (till) - silty, sandy, grey, stiff, wet with pebbles
12.5' - 14'
EXPLORATION DEPTH (4.3 m)
STANDPIPE INSTALLED TO 4.1 m
AN-GEO ENVIRONMENTAL CONSULTANTS LTD.
EDMONTON, ALBERTA
LOGGED BY: DH
REVIEWED BY: PM
FIGURE NO.: 11
COMPLETION DEPTH: 4.3 m
DATE: 97-07-31
PAGE: B11 of B15

Hydrogeology/Remediation Feasibility Study Funnel and Gate Option 4 Wing Cold Lake, Alberta	CLIENT: Defence Construction Canada	BOREHOLE NO.: BH 212
	DRILL: Mobile Augers	JOB NO.: 010-A003-01
		ELEVATION: 536.38 m

SAMPLE TYPE: SHELBY | DISTURBED | SPLIT SPOON | NO RECOVERY | A CASING | CORE

DEPTH m	DEPTH ft	SOIL DESCRIPTION	SAMPLE TYPE (NO.)	SPLIT SPOON INTERVAL	● STANDARD PENETRATION COUNT ● / ○ DYNAMIC CONE COUNT ○ (10 20 30 40)	WELL
		Surface - 4 " - vegetation, wood pieces, organics				
1		13 " Recovery - 3 " - organics, roots 10 " - sand, silty, fine to medium, compact, moist		2.5 ' - 4 '		
	5	17 " Recovery - 15 " - sand, silty, fine to medium, very loose, wet 2 " - clay (till) - silty, olive, soft		5 ' - 6.5 '		
2						
		17 " Recovery - clay (till) - silty, olive grey, soft to medium, moist with pebbles		7.5 ' - 9 '		
3	10	10 " Recovery - clay (till) - sandy, olive grey, medium, moist with pebbles		10 ' - 11.5 '		
4		10 " Recovery - clay (till) - sandy, olive grey, stiff, moist with pebbles		12.5 ' - 14 '		
	15	EXPLORATION DEPTH (4.3 m) STANDPIPE INSTALLED TO 4.3 m				
5						
6	20					
7						
	25					
8						
9	30					
10						
	35					

AN-GEO ENVIRONMENTAL CONSULTANTS LTD. EDMONTON, ALBERTA	LOGGED BY: DE	COMPLETION DEPTH: 4.3 m
	REVIEWED BY: PM	DATE: 97-07-31
	FIGURE NO.: 12	PAGE: B12 of B15


TM ZONE: - N 21036.45 E546056.31
Mobile Augers Driller: Ken Bieber
BOREHOLE No: AH-02
PROJECT ENGINEER:
Wheeled auger Rig "Mori 10"
Project No: Landfill
Mobile Augers Driller: Ken Bieber
6" Solid Stem bit, drilled dry
ELEVATION: 539.574 (m)
SAMPLE TYPE
DISTURBED
NO RECOVERY
SPT
A-CASING
SHELBY TUBE
CORE
DEPTH (m)
USC
SOIL SYMBOL
STRATIGRAPHY
SAMPLE TYPE
SAMPLE NO
SPT(N)
LEL (%)
BTEX (mg/L)
DWAPL (mg/L)
WELL INSTALLATION
Comments
ELEVATION(m)
Topsoil (OL), disturbed with roots, loose black no odour
Sand (SP), moderately to strongly oxidized, no odour
Silty Sand (SM), subangular gravel, no odour
Same as above
Silty Sand (SM), loose, trace coarse sand, dark grey, moist, no odour, clasts to 3cm
0083
0.00
0.00
0.00
Hole backfilled with cuttings
539.6
536.6
533.6
Clay (CI), medium plasticity, grey, uniform, no odour, dry
moist, higher dry strength, trace coarse
Clay (CH), high plasticity, grey no odour, gravel
End of hole at 3.81m (12.5 feet)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
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LOGGED BY: AM CAJ
REVIEWED BY: KWB
Fig. No:
COMPLETION DEPTH: 4.0
COMPLETE: 98/08/13
Page 1 of 1

TM ZONE: - N 21274.06 E546018.17	Mobile Augers Driller: Ken Bieber		BOREHOLE No: AH-03
PROJECT ENGINEER:	Wheeled uger Rig "Mori 10"		Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry		ELEVATION: 537.763 (m)
SAMPLE TYPE: DISTURBED / NO RECOVERY / SPT / A-CASING / SHELBY TUBE / CORE			

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	OL		Topsoil (OL), disturbed, loose									537.8
	SP		no odour									
	SP		Sand (SP), coarse, oxidized, no odour									
	SP		Sand (SP), coarse, very red, dry, no odour									
1.0	SM		Silty Sand (SM), medium, coarse, moist, no odour								Hole backfilled with cuttings	
	SM		Silty Sand (SM), fine, loose, saturated,									
2.0	SM		no odour		0084		0.00	0.00	0.00			
			Silty Sand (SM), coarse, dry, some coarse grain, more coarse grain at bottom									
3.0												534.8
			End of hole at 2.23m (7.5 feet)									
4.0												
5.0												
6.0												531.8
7.0												
8.0												

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LOGGED BY: AM CAJ
REVIEWED BY: KWB
Fig. No:

COMPLETION DEPTH: 2.2
COMPLETE: 98/08/13
Page 1 of 1

TM ZONE: - N 21335.94 E546095.28	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-04
PROJECT ENGINEER:	Wheeled auger Rig "Mark 10"	Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry	ELEVATION: 537.463 (m)

SAMPLE TYPE: DISTURBED | NO RECOVERY | SPT | A-CASING | SHELBY TUBE | CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	SM		Silty Sand (SM), medium, loose, gravel to 35mm, subrounded, no odour, moist throughout									537.5
1.0	SM										Hole backfilled with cuttings	
	SM		Silty Sand (SM), medium, loose, no odour more moist than above									
	SM		Silty Sand (SM), medium to fine		0085			0.00	0.00			
2.0	SM		Silty Sand (SM), fine, trace wood and organic material, grey to black, marshy odour, very moist									
	CL		Clay (CL), loose, no odour, moist									534.5
3.0	CL		Sandy Clay (CL), loose, no odour, moist									
	CL		Clay (CL), medium, gritty, some gravel, no odour, moist									
4.0			End of hole at 3.81m (12.5 feet)									
5.0												
6.0												531.5
7.0												
8.0												

University of Alberta

LOGGED BY: AM CAJ | COMPLETION DEPTH: 0.0
REVIEWED BY: KWB | COMPLETE: 98/08/13
Fig. No: | Page 1 of 1

IN ZONE: -- N 21299.32 E546126.10	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-05
PROJECT ENGINEER:	Wheeled auger Rig "Marl 10"	Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry	ELEVATION: 537.511 (m)

SAMPLE TYPE: DISTURBED | NO RECOVERY | SPT | A-CASING | SHELBY TUBE | CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	SM		Silty Sand (SM), medium, loose, gravel to 35mm, subrounded, no odour, moist									537.5
1.0	SM		clean, more oxidized than above, more Silty Sand (SM), coarser than above, organic material, no odour, moist								Hole backfilled with cuttings	
	SM		Silty Sand (SM), same as above, very wet									
2.0	SM		Silty Sand (SM), finer, oxidized, no odour, wet		0086			0.00	0.00			
	SM		Silty Sand (SM), medium, more silt than above, no odour, wet									
3.0	CL		organic material, grey to black, marshy odour, very moist									534.5
			Clay (CL), loose, no odour, moist									
			Silty Sand (SM), fines, sand and silt, very wet									
	CL		Silty Sand (SM), same as above									
4.0			Clay (CL), low plasticity, brown, organic odour, dry									
			Clay (CL), low plasticity, grey, black on inside of core, some pebbles, coarse towards bottom, organic odour, moist									
5.0			End of hole at 3.81m (12.5 feet)									
6.0												531.5
7.0												
8.0												

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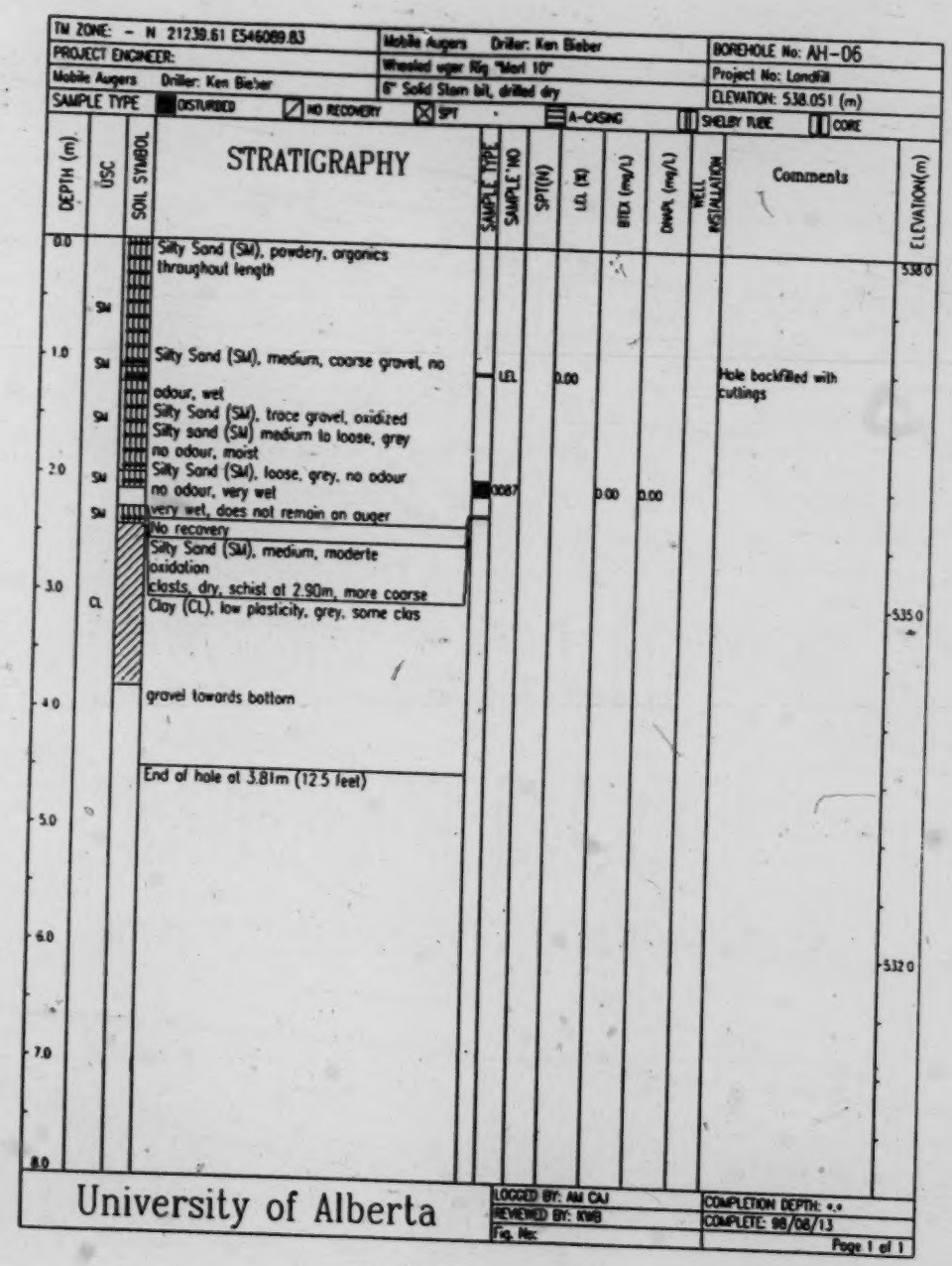
LOGGED BY: AM CAJ | COMPLETION DEPTH: 0.0
REVIEWED BY: KWB | COMPLETE: 98/08/13
Fig. No: | Page 1 of 1



TM ZONE: - N 21239.61 E546089.83
Mobile Augers Driller: Ken Bieber
BOREHOLE No: AH-06
PROJECT ENGINEER:
Wheeled auger Rig "Merl 10"
Project No: Landfill
Mobile Augers Driller: Ken Bieber
6" Solid Stem bit, drilled dry
ELEVATION: 538.051 (m)
SAMPLE TYPE DISTURBED NO RECOVERY SPT A-CASING SHELBY TUBE CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	SM		Silty Sand (SM), powdery, organics throughout length									538.0
1.0	SM		Silty Sand (SM), medium, coarse gravel, no odour, wet		LEL		0.00				Hole backfilled with cuttings	
	SM		Silty Sand (SM), trace gravel, oxidized									
	SM		Silty sand (SM) medium to loose, grey no odour, moist									
2.0	SM		Silty Sand (SM), loose, grey, no odour									
	SM		no odour, very wet		0087			0.00	0.00			
			very wet, does not remain on auger									
			No recovery									
3.0			Silty Sand (SM), medium, moderte oxidation									
	CL		clasts, dry, schist at 2.90m, more coarse									
			Clay (CL), low plasticity, grey, some clas									535.0
4.0			gravel towards bottom									
			End of hole at 3.81m (12.5 feet)									
5.0												
6.0												532.0
7.0												
8.0												

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REVIEWED BY: KWB
Fig. No:
COMPLETION DEPTH: 4.0
COMPLETE: 98/08/13
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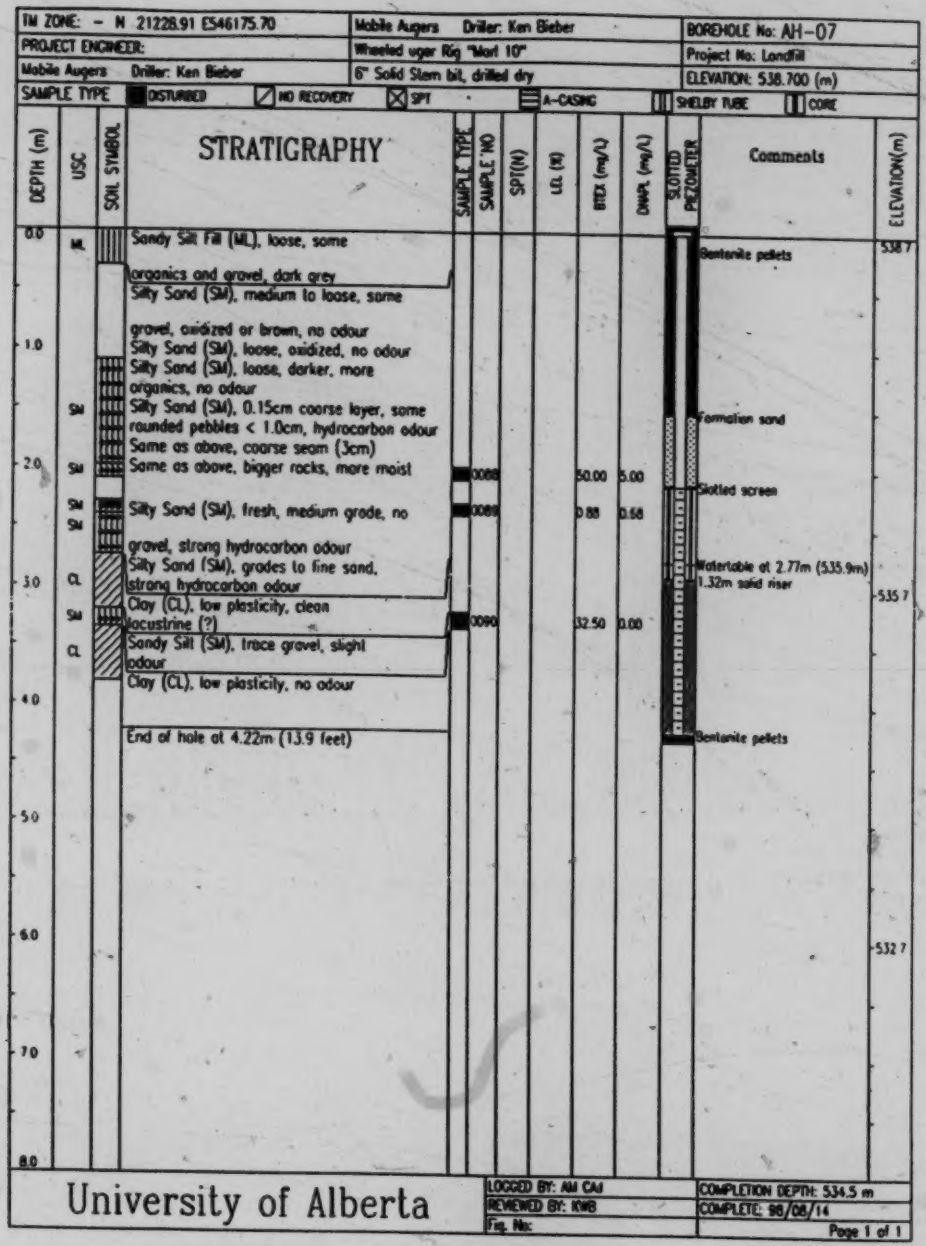
TM ZONE: - N 21228.91 E546175.70
Mobile Augers Driller: Ken Bieber
BOREHOLE No: AH-07
PROJECT ENGINEER:
Wheeled uger Rig "Marl 10"
Project No: Landfill
Mobile Augers Driller: Ken Bieber
6" Solid Stem bit, drilled dry
ELEVATION: 538.700 (m)
SAMPLE TYPE
DISTURBED
NO RECOVERY
SPT
A-CASING
SHELBY TUBE
CORE
DEPTH (m)
USC
SOIL SYMBOL
STRATIGRAPHY
SAMPLE TYPE
SAMPLE NO
SPT(N)
LEL (%)
BTEX (mg/L)
DNAPL (mg/L)
SLOTTED PIEZOMETER
Comments
ELEVATION(m)
Sandy Silt Fill (ML), loose, some organics and gravel, dark grey
Silty Sand (SM), medium to loose, some gravel, oxidized or brown, no odour
Silty Sand (SM), loose, oxidized, no odour
Silty Sand (SM), loose, darker, more organics, no odour
Silty Sand (SM), 0.15cm coarse layer, some rounded pebbles < 1.0cm, hydrocarbon odour
Same as above, coarse seam (3cm)
Same as above, bigger rocks, more moist
Silty Sand (SM), fresh, medium grade, no gravel, strong hydrocarbon odour
Silty Sand (SM), grades to fine sand, strong hydrocarbon odour
Clay (CL), low plasticity, clean lacustrine (?)
Sandy Silt (SM), trace gravel, slight odour
Clay (CL), low plasticity, no odour
End of hole at 4.22m (13.9 feet)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
ML
SM
SM
SM
CL
SM
CL
0088
0089
0090
50.00
0.88
32.50
5.00
0.68
0.00
Bentonite pellets
Formation sand
Slotted screen
Watertable at 2.77m (535.9m)
1.32m solid riser
Bentonite pellets
538.7
535.7
532.7
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LOGGED BY: AM CAI
REVIEWED BY: KWB
Fig. No:
COMPLETION DEPTH: 534.5 m
COMPLETE: 98/08/14
Page 1 of 1

TM ZONE: - N 21230.69 E546174.27	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-08
PROJECT ENGINEER:	Wheeled auger Rig "Mori 10"	Project No: Landfill
Mobile Augers Driller: Ken Bieber	5" Hollow Stem BR, drilled dry	ELEVATION: 538.790 (m)

SAMPLE TYPE: DISTURBED | NO RECOVERY | SPT | A-CASING | SHELBY TUBE | CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	SLOTTED PIEZOMETER	Comments	ELEVATION(m)
0.0	ML		Sandy Silt Fill (ML), loose, some organics and gravel, dark grey								Grout (to 7.19m)	538.8
1.0			Silty Sand (SM), medium to loose, some gravel, oxidized or brown, no odour									
			Silty Sand (SM), loose, oxidized, no odour									
			Silty Sand (SM), loose, darker, more organics, no odour									
2.0	SM		Silty Sand (SM), 0.15cm coarse layer, some rounded pebbles < 1.0cm, hydrocarbon odour									
	SM		Same as above, coarse seam (3cm)									
			Same as above, bigger rocks, more moist									
3.0	CL		Silty Sand (SM), fresh, medium grade, no gravel, strong hydrocarbon odour									535.8
	SM		Silty Sand (SM), grades to fine sand, strong hydrocarbon odour									
	CL		Clay (CL), low plasticity, clean lacustrine (?)									
4.0			Sandy Silt (SM), trace gravel, slight odour									
5.0			Clay (CL), low plasticity, no odour									
			Silty Clay Till with Sand (CL), uniform some pebbles throughout, up to 5mm, dark grey, no odour, a little moisture									
6.0	CL		1mm of fine sand at 4.57m									532.8
			Silty Clay Till (CL), same as above, slightly more sand									
7.0			Silty Clay Till (CL), more sand, dark grey, no odour, moist from 4.72 to 4.88m									
			Silty Clay Till (CL), uniform, some pebbles throughout, up to 5mm, dark grey, no odour, drier than above								Bentonite (to 7.79m)	
8.0	CL		Silty Clay Till (CL), trace gravel, subrounded, clasts up to 3cm, no structure, clean, somewhat dry		LEL	0.00					Formation Sand (to 10.52m)	
			Pushed rock, recovered 0.30m, same above									
9.0	CL		A-Casing to push stone, pushed ~0.61m, now at 7.32m									529.8
			Put SPT, now at 8.23m, some structure as above, bigger rocks, medium gravel, no odour		LEL	0.00						
10.0	CL		Drill with plug, no recovery, drilling with 5 hollow stem									
											Slotted Screen	
11.0	SM		Silty Sandy Till (CL), very dense, some cobbles up 8cm, dark grey, no odour		0098		0.00	0.00			Watertable at 11.0m (527.8m)	
			1mm sand seam at 8.39m								Formation Sand	
			Same as above, lighter colour at bottom, slight hydrocarbon odour, driller sees									

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REVIEWED BY: KWB
Fig. No:

COMPLETION DEPTH: 527.4 m
COMPLETE: 98/08/15

TM ZONE: - N - E -	Mobile Augers Driller: Ken Bieber		BOREHOLE No: AH-09
PROJECT ENGINEER:	Hodwell Auger		Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry		ELEVATION: 0.000 (m)
SAMPLE TYPE ■ DISTURBED ⧄ NO RECOVERY ⊠ SPT ▭ A-CASING ▯ SHELBY TUBE ▯ CORE			

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DWPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	OL		Organic mat (OL), saturated, rootlets wood fragments, black, moist, water at surface									0.0
	ML		Sandy Silt (ML) with trace coarse sand and gravel, wet									
1.0	SM		Silty fine-medium Sand (SM), some clay and a lot of organic material, trace gravel, up to 2cm, subrounded, loose, dark grey to black								Hole backfilled with cuttings	
			Clay at base									
2.0	SM		Clayey Silty Sand (SM/SC), some roots, fin fine sand quickly grades into silt, trace gravel, loose, oxidized around roots									
			Same as above, mosit not wet, slightly stronger									
			Same as above, greyish/green colour									
3.0			Same as above, more pebbles, much stifer a little modeled, weathered stones, no odour, slightly oxidized									-3.0
4.0			End of hole at 3.81m (12.5 feet)									
5.0												
6.0												-6.0
7.0												
8.0												

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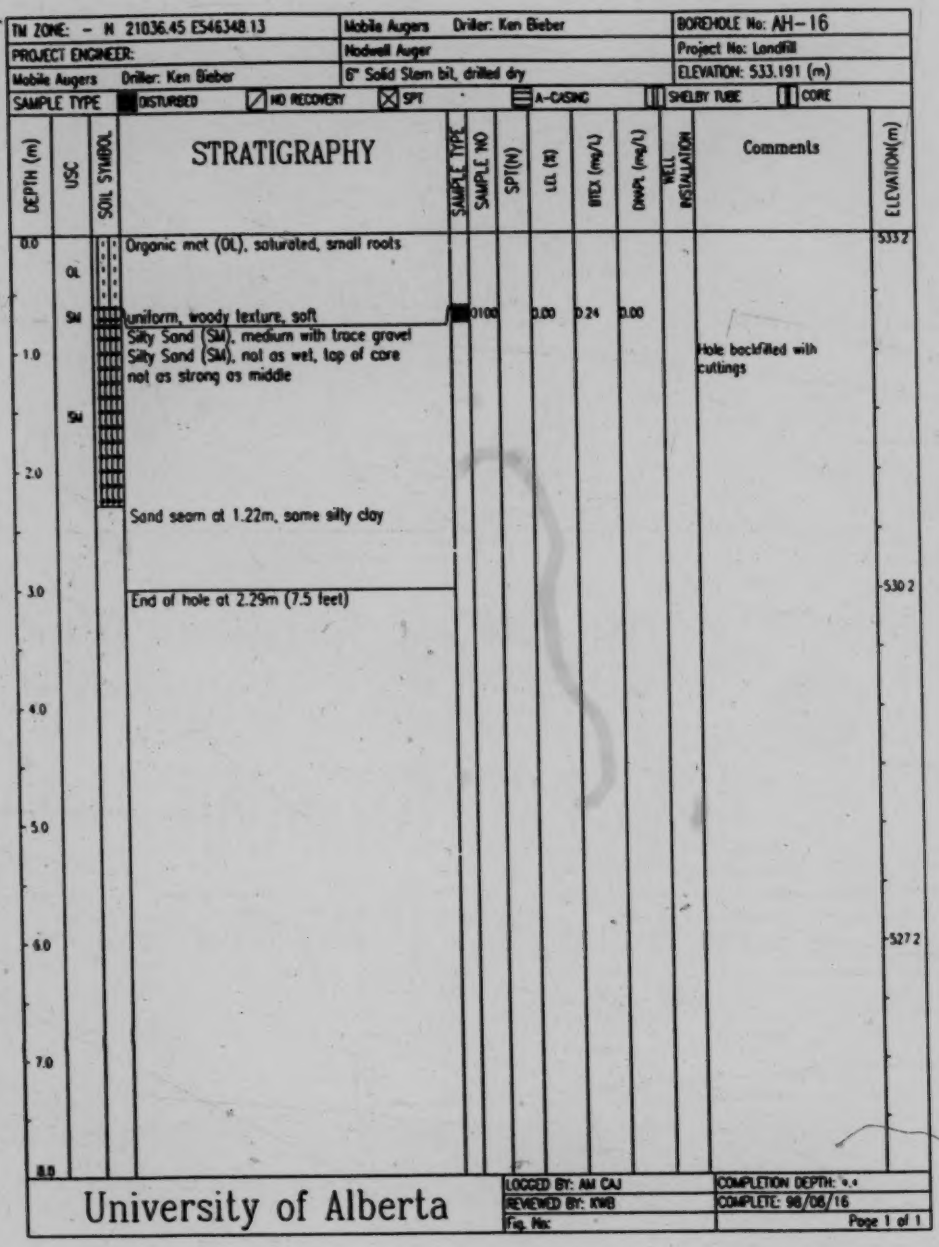
LOGGED BY: AM CAJ
REVIEWED BY: KWB
Fig. No:

COMPLETION DEPTH: 0.0
COMPLETE: 98/08/15


TM ZONE: - N 21036.45 E546348.13
Mobile Augers Driller: Ken Bieber
BOREHOLE No: AH-16
PROJECT ENGINEER:
Nodwell Auger
Project No: Landfill
Mobile Augers Driller: Ken Bieber
6" Solid Stem bit, drilled dry
ELEVATION: 533.191 (m)
SAMPLE TYPE
DISTURBED
NO RECOVERY
SPT
A-CASING
SHELBY TUBE
CORE
DEPTH (m)
USC
SOIL SYMBOL
STRATIGRAPHY
SAMPLE TYPE
SAMPLE NO
SPT(N)
LEL (%)
BTEX (mg/L)
DNAPL (mg/L)
WELL INSTALLATION
Comments
ELEVATION(m)
0.0
OL
Organic mat (OL), saturated, small roots
533.2
SM
uniform, woody texture, soft
0100
0.00
0.24
0.00
1.0
Silty Sand (SM), medium with trace gravel
Silty Sand (SM), not as wet, top of core not as strong as middle
Hole backfilled with cuttings
SM
2.0
Sand seam at 1.22m, some silty clay
3.0
End of hole at 2.29m (7.5 feet)
530.2
4.0
5.0
6.0
527.2
7.0
8.0
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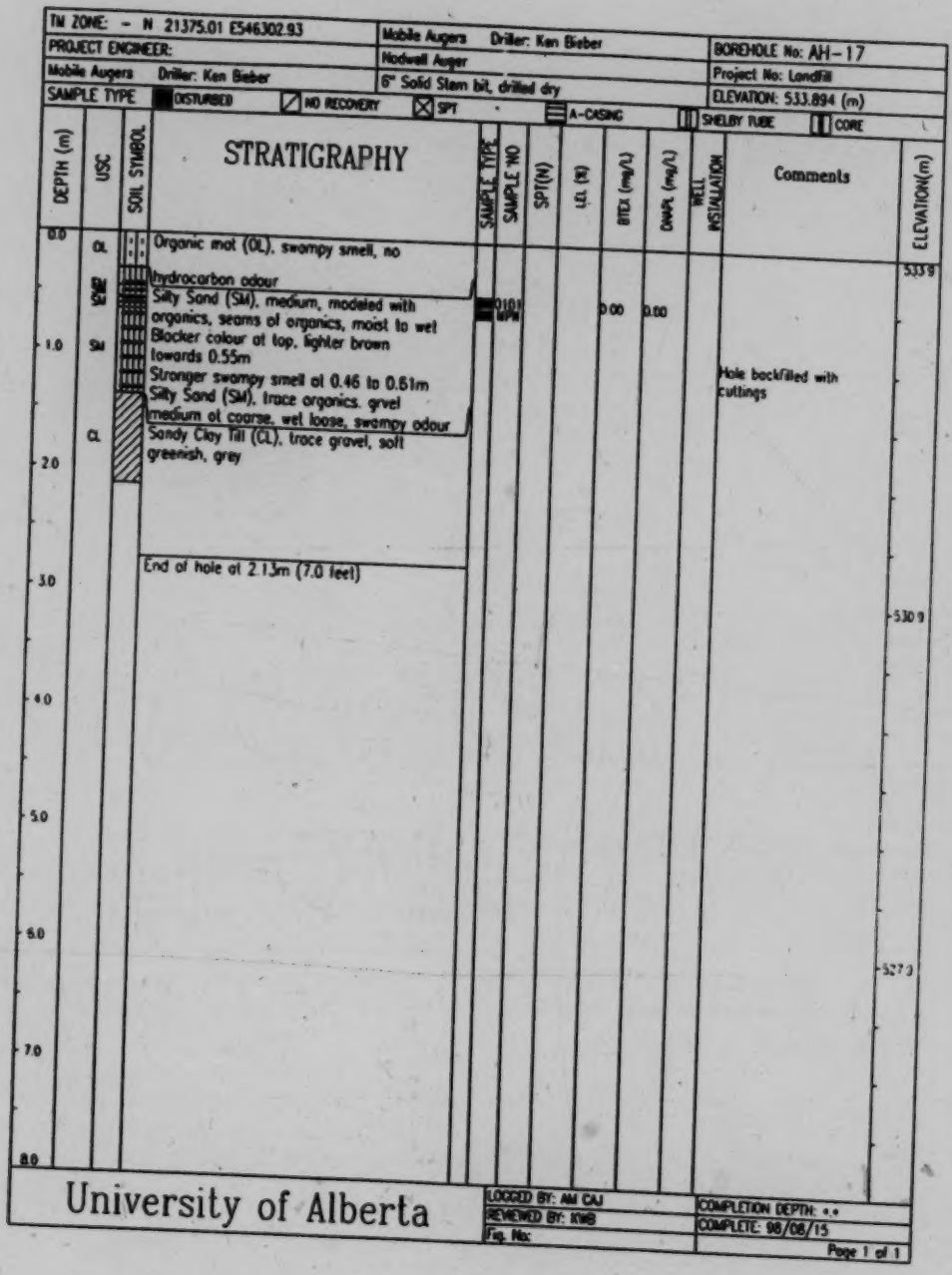
LOGGED BY: AM CAJ
REVIEWED BY: KWB
Fig. No:
COMPLETION DEPTH: 0.0
COMPLETE: 98/08/16
Page 1 of 1


TM ZONE: - N 21375.01 E546302.93
Mobile Augers Driller: Ken Bieber
BOREHOLE No: AH-17
PROJECT ENGINEER:
Hodwell Auger
Project No: Landfill
Mobile Augers Driller: Ken Bieber
6" Solid Stem bit, drilled dry
ELEVATION: 533.894 (m)
SAMPLE TYPE
DISTURBED
NO RECOVERY
SPT
A-CASING
SHELBY TUBE
CORE
DEPTH (m)
USC
SOIL SYMBOL
STRATIGRAPHY
SAMPLE TYPE
SAMPLE NO
SPT(N)
LEL (%)
BTEX (mg/L)
DNAPL (mg/L)
WELL INSTALLATION
Comments
ELEVATION(m)
Organic mat (OL), swampy smell, no hydrocarbon odour
Silty Sand (SM), medium, modeled with organics, seams of organics, moist to wet
Blacker colour at top, lighter brown towards 0.55m
Stronger swampy smell at 0.46 to 0.61m
Silty Sand (SM), trace organics, grvel
medium at coarse, wet loose, swampy odour
Sandy Clay Till (CL), trace gravel, soft greenish, grey
End of hole at 2.13m (7.0 feet)
Hole backfilled with cuttings
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
533.9
530.9
527.9
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LOGGED BY: AM CAI
REVIEWED BY: KWB
Fig. No:
COMPLETION DEPTH: **
COMPLETE: 98/08/15
Page 1 of 1

TM ZONE: - N 21410.45 E546347.62	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-18
PROJECT ENGINEER:	Mcdwell Auger	Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry	ELEVATION: 532.754 (m)

SAMPLE TYPE: DISTURBED | NO RECOVERY | SPT | A-CASING | SHELBY TUBE | CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DWPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	OL		Organic mat (OL), swampy smell, no hydrocarbon odour									532.8
			At 0.46m, sandy with trace gravel organic rich									
	SM		Silty Sand(SM), clean, loose, grey-green									
1.0			At 0.84m (2.75 feet), more clayey								Hole backfilled with cuttings	
	CL		Sandy Silty Till (CL), a little modeled, few sandy pockets, < 1cm (rare), very cold, grey									
2.0												
3.0			End of hole at 2.44m (8.0 feet)									529.8
4.0												
5.0												
6.0												525.8
7.0												
8.0												

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LOGGED BY: AM CAJ | COMPLETION DEPTH: 0.0

REVIEWED BY: KWB | COMPLETE: 98/08/15

Fig. No: | Page 1 of 1

TM ZONE: - N 21375.08 E546264.24	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-19
PROJECT ENGINEER:	Wheeled auger Rig "Mori 10"	Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry	ELEVATION: 534.141 (m)

SAMPLE TYPE: DISTURBED | NO RECOVERY | SPT | A-CASING | SHELBY TUBE | CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	SM		Silty Sand (SM), with some clayey, dry light brown, fine-medium grained, some organics mixed in, loose									534.1
	CL		Silty Sandy Clay (CL), with trace organics mat, light to dark brown, loose to slightly compacted, mottled									
1.0	SM		Silty Sand (SM), fine, some mottled organics, loose, trace gravel, darkening and becoming homogeneous								Hole backfilled with cuttings	
	SW		Dark grey medium sand up to 1.52m									
			Same as above, medium-coarse, loose, no bedding evident, light grey, strong		Rate							
2.0	SM		hydrocarbon odour									
	SM		Same as above, hit water between 2.14 and 2.29m, more fines and sloppy		0244			5.30	1.21			
	SM		Fine Silty Sand (SM), loose, homogeneous saturated, green-grey									
3.0			Same as above, medium-fine silty sand									531.1
	CL		Clay Till (CL), silt and sand, dense to compact, trace gravel, saturated, dark grey									
4.0			End of hole at 3.81m (12.5 feet)									
5.0												
6.0												528.1
7.0												
8.0												

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LOGGED BY: AM CAJ
REVIEWED BY: KMB
Fig. No:

COMPLETION DEPTH: 3.81m
COMPLETE: 98/10/05
Page 1 of 1

TM ZONE: - N 21163.70 E546111.03	Mobile Augers Driller: Ken Bieber	BOREHOLE No: AH-20
PROJECT ENGINEER:	Wheeled ugar Rig "Mari 10"	Project No: Landfill
Mobile Augers Driller: Ken Bieber	6" Solid Stem bit, drilled dry	ELEVATION: 538.647 (m)

SAMPLE TYPE ■ DISTURBED ⁄ NO RECOVERY ⊠ SPT · ☰ A-CASING ▯ SHELBY TUBE ▯ CORE

DEPTH (m)	USC	SOIL SYMBOL	STRATIGRAPHY	SAMPLE TYPE	SAMPLE NO	SPT(N)	LEL (%)	BTEX (mg/L)	DNAPL (mg/L)	WELL INSTALLATION	Comments	ELEVATION(m)
0.0	SM		Silty Sand (SM), medium grained sand, loose, moist, trace gravel, medium brown, no odour									538.7
1.0	SP		Sand (SP), medium grained, loose, some silt, rare gravel, greenish grey, homogeneous, STRONG hydrocarbon odour								Hole backfilled with cuttings	
2.0			Water table at 2.13m (7.0 feet), sloppy									
	SM		slightly finer grained	■	0245			9.88				
			Same as above, medium grained, black and thick free-product, very strong hydrocarbon odour					2.50	0.42			
3.0	CL		Clay Till (CL), silt and sand, compact heterogeneous, green gray at contact and moderately strong odour decreasing with depth									535.7
4.0												
			End of hole at 3.81m (12.5 feet)									
5.0												
6.0												532.7
7.0												
8.0												

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REVIEWED BY: KWB
Fig. No:

COMPLETION DEPTH: 0.0
COMPLETE: 98/10/05
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APPENDIX C:

Analytical Test Methods

Test Methodologies

Acid Digestion

Preparation: Microwave digestion of sample in a closed vessel with concentrated nitric acid on water samples.
Reference: E.P.A. SW 846 Method 3015

Balance

Instrumental Method: Sum(Anions)/Sum(Cations)*100
Method Reference: APHA 1030 F

Bicarbonate (HCO3)

Instrumental Method: Calculated from Alkalinity
Method Reference: APHA 2320B

BTEX in Water

PREPARATION METHOD: Purge and trap extraction.

INSTRUMENTAL METHOD: GC/PID

METHOD REFERENCE: Modified SW-846 USEPA Method 5030 and 8020.

QC SUMMARY:

Accuracy	Precision
100%	+/- 10%

NOTE: Accuracy is expressed as the average % recovery and Precision as the relative standard deviation (RSD) of fortifications made using certified standards (BTEX).

BTEX and TVH in Soil

PREPARATION METHOD: Methanol extraction with headspace analysis.

INSTRUMENTAL METHOD: GC/PID for BTEX.
GC/PID for TVH - summation of hydrocarbons from C5 to C10 carbon range and is calculated against a BTEX standard.
NOTE: Results based upon dry weight.

METHOD REFERENCE: Modified SW-846 USEPA Method 5021 and 8015/8020.

BTEX QC SUMMARY:

Accuracy	Precision
93%	+/- 23%

NOTE: Accuracy is expressed as the average % recovery and Precision as the relative standard deviation (RSD) of fortifications made using certified standards (BTEX).

TVH QC SUMMARY:

Accuracy	Precision
96%	+/- 24%

NOTE: Accuracy is expressed as the average % recovery and Precision as the relative standard deviation (RSD) of fortifications made using certified standards (BTEX).

Chloride (Cl)

Preparation: Filter through 0.45u filter
Instrumental: Sample analyzed colorimetrically @ 480 nm using ferricyanide method on a Cobas Fara discrete analyzer
Reference: APHA 4500-Cl, E

Test Methodologies

or

Preparation Method: 0.45µ filtration if turbid
Instrumental Method: Ion Chromatography
Method Reference: APHA 4110 B

Carbonate (CO3)

Instrumental Method: Calculated from Alkalinity
Method Reference: Carbonate APHA 2320B

Conductance (EC)

Instrumental Method: Conductivity Meter
Method Reference: Conductance APHA 2510B

Ferrous Iron, Extractable

Preparation: Preserve with HCl to pH <4, store in vial with no headspace.
Instrumental: The sample is analyzed by IC with a UV/VIS detector and PAR color reagent. Alternatively, for high values, the extract is analyzed also by ICP, and the ferrous iron is determined by difference (ICP Fe - Fe+3)
Method Reference: Dionex Technical Note #10

Ferric Iron, HCL Extract.

Preparation: 10 g of wet soil is sonicated for 1 hour with 50 ml 1N HCl extracting solution under a nitrogen blanket.
Instrumental: The extractant is analyzed by IC with a UV/VIS detector and PAR color reagent. Alternatively, for high values, the extract is analyzed also by ICP, and the ferric iron is determined by difference (ICP Fe - Fe+2)
Method Reference: Dionex Technical Note #10

Hardness

Instrumental Method: Calculated from Ca+Mg as CaCO3
Method Reference: Hardness APHA 2340 B

ICP Metals Setup

PREPARATION METHOD:

Dissolved: Filter through 0.45u and preserve with nitric acid
Extractable: Preserve with nitric acid
Total: Preserve with nitric acid; digest with nitric/hydrochloric acid

INSTRUMENTAL METHOD: ICP Spectrophotometry
METHOD REFERENCE: APHA 3120B/3030F, Standard Methods; 18th ed.

Routine Metals

PREPARATION METHOD: Filter through 0.45u and preserve with nitric acid
INSTRUMENTAL METHOD: ICP Spectrophotometry
METHOD REFERENCE: APHA 3120B/3030F, Standard Methods; 18th ed.

Test Methodologies

Sulfur reported as sulfate. ICP result multiplied by 3 to convert.

Sulfate (SO4)

Preparation Method: 0.45 u filtraton if turbid
Instrumental Method: Ion Chromatography or ICP
Method Reference: SO4 Dionex Handbook of Ion Chromatography pg 37.

% Moisture

Preparation Method: Sample is oven dried at 105 degrees C
Instrumental Method: Gravimetric analysis

Nitrate+Nitrite (N)

Preparation Method: 0.45µ Filtration
Instrumental Method: Automated colorimetry (Cobas Fara Discrete analyzer)
Hydrazine reduction @ 520 nm
Method Reference: APHA 4500-NO3-H

or

Preparation Method: 0.45µ filtration if turbid
Instrumental Method: Ion Chromatography
Method Reference: APHA 4110 B
and
Preparation Method: 0.45µ filtration if turbid
Instrumental Method: Ion Chromatography
Method Reference: APHA 4110 B

Hydroxide

Method Reference: Hydroxide APHA 2320 B

pH in Water

Instrumental Method: pH Meter
Method Reference: APHA 4500-H+ B

Sulphide

Instrumental Method: Automated continuous flow with dialysis
and colorimetry at 600 nm
Method Reference: Sulphide

Total Alkalinity

Instrumental Method: If pH<8.3 on the initial sample, titration for alkalinity will be performed to pH 8.3 and 4.5 endpoint, using autotitrator or manual technique.

Method Reference: T ALK APHA 2320B

TDS (Calculated)

Instrumental Method: Calculated from the sum of ions
Method Reference: TDS APHA 1030 F

Test Methodologies

Total Extractables (Soil)

PREPARATION METHOD: Shake and sonication extraction with organic solvent

INSTRUMENTAL METHOD: GC/FID - summation of hydrocarbons from C11 to C30 carbon range (excluding benzene, toluene, ethylbenzene, and xylenes) and calculated against diesel standard.
NOTE: Results based upon dry weight.

METHOD REFERENCE: Modified SW-846 USEPA Method 3550/3580 and 8000

QC SUMMARY:

Accuracy	Precision
111%	+/- 24%

NOTE: Accuracy is expressed as the average % recovery and Precision as the relative standard deviation (RSD) of fortifications made using in-house standards (TEH).

Total Kjeldahl Nitrogen

Total Organic Carbon

Instrumental Method: Combustion - Infrared carbon analyzer

Phosphorus, Total

Preparation Method: Persulphate/ Sulfuric Acid tube digest
Instrumental Method: Automated colorimetry (Cobas Fara discrete analyzer) Asorbic acid reduction
Method Reference: Phosphorous, Total APHA 4500-P B,E
Cobas Fara II water testing Application

Vol. Organics (MS):Solids

Preparation Method: Automated headspace

Instrument Method: GC/MS analysis

Method Reference: Extraction Method: EPA 5021 (modified)
Analytical Method: EPA 8240 (modified)

Interferences: *** Values for 1,1,2,2-tetrachloroethane and trichloroethene may not accurately reflect concentrations present in the sample(s) due to the decomposition of the former to the latter when exposed to heat and pressure. (See MOEE Method PETHC-E3132A, 1.5.1.5 Dehydrohalogenation)

Volatile Organics (MS):H20

Preparation Method: Automated headspace

Instrument Method: GC/MS analysis

Method Reference: Extraction Method: EPA 5021 (modified)
Analytical Method: EPA 8240 (modified)

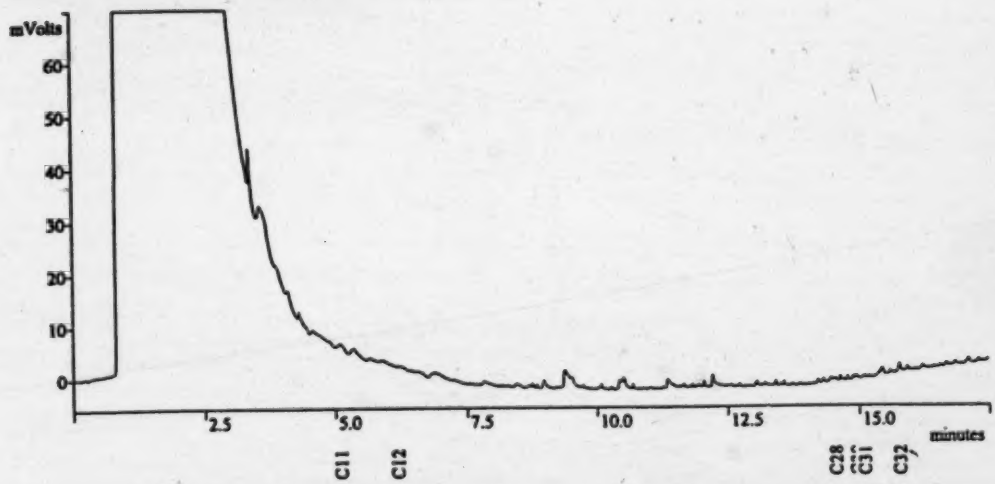
Interferences: *** Values for 1,1,2,2-tetrachloroethane and trichloroethene

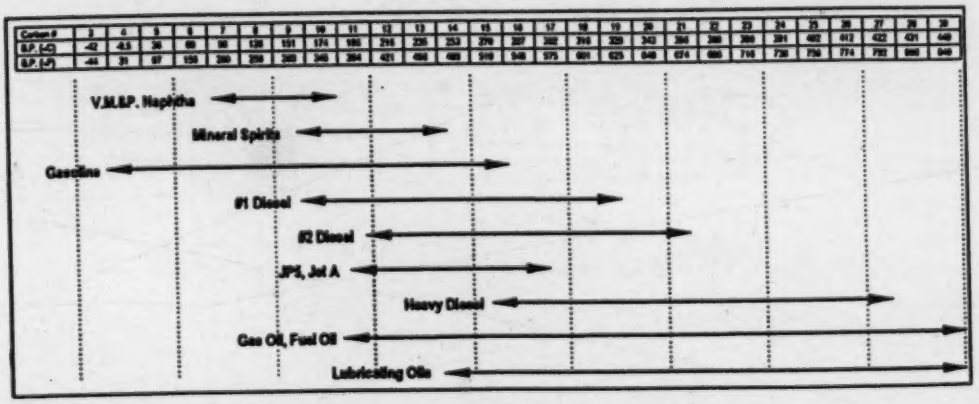
may not accurately reflect concentrations present in the sample(s) due to the decomposition of the former to the latter when exposed to heat and pressure. (See MOEE Method PETHC-E3132A, 1.5.1.5 Dehydrohalogenation)

THIS IS THE LAST PAGE OF THE METHODOLOGY APPENDIX.

CLIENT I.D.: 980071

Data File:	c:\star\module16\aug712.run
Sample ID:	E808704-14A-10
Injection Date:	08/21/98 12:32:14 PM
Instrument (Inj):	Varian Star 3400CX



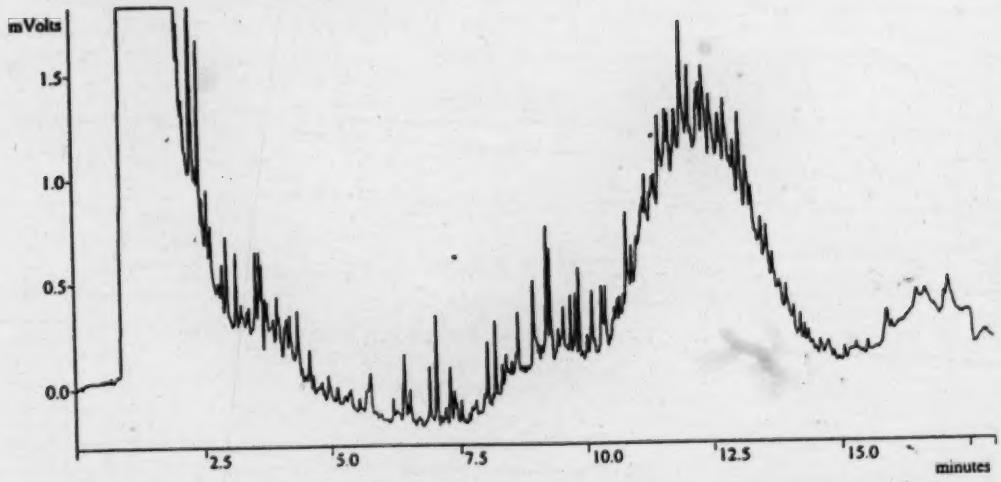


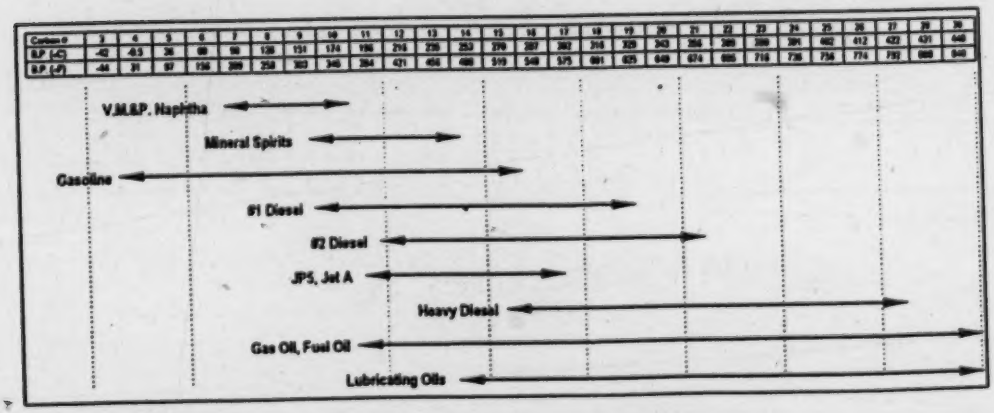
Boiling Point Distribution Range for Petroleum Based Fuel Products

Adapted from: Drews, A.W., ED; Manual on Hydrocarbon Anaysis, 4th ed.; American Society for Testing and Materials: Philadelphia, PA, 1989: p XVIII.

CLIENT I.D.: 980074

Data File:	c:\star\module16\auga841.run
Sample ID:	E808704-16A-10 RW
Injection Date:	08/27/98 10:19:28 PM
Instrument (Inj):	GC 3600 SIDE A





Boiling Point Distribution Range for Petroleum Based Fuel Products

Adapted from: Drews, A.W., ED; Manual on Hydrocarbon Anaysis, 4th ed.; American Society for Testing and Materials: Philadelphia, PA, 1989: p XVIII.

APPENDIX D:

Gas Chromatograph Specifications and Methane Analysis

SPECIFICATIONS FOR GAS CHROMATOGRAPH USED FOR METHANE ANALYSIS

HP 5700, Flame Ionization Detector

Detector Temperature: 250°C

Oven Temperature: 35°C

Injection Temperature: 0°C

Ambient Temperature: 26°C

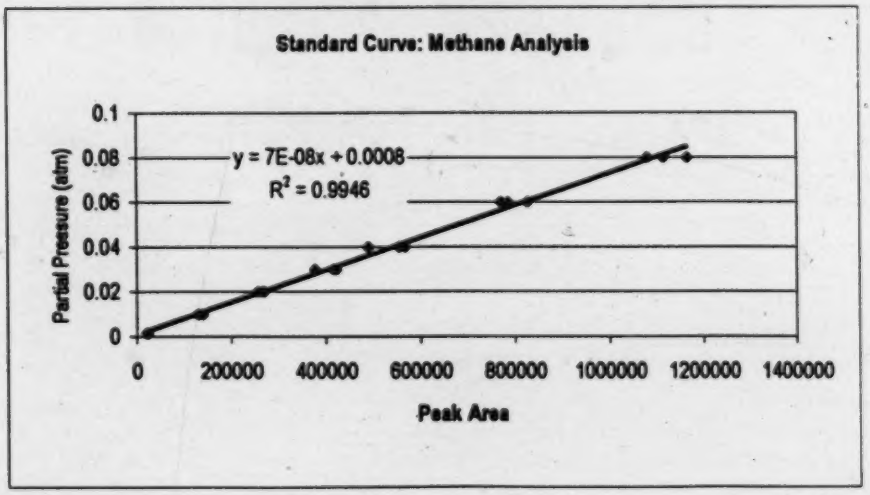
Column: Tenex GC, 60/80 Resin Mesh, Uncoated 6' long

Flow Rates:		
	Helium	35 mL/min
	Air	327 mL/min
	Nitrogen	49.5 mL/min

METHANE STANDARD CURVE: AUGUST 6-17th SAMPLING

Temperature (deg C):	25
Henry's Constant (atm*L/mol):	13.411×10^{-4}
ρ CH_4 (g/L):	0.7174
MW (g/moL)	16.04
mol air:	0.006711
Assume STP	1 atm 0 deg C

% CH_4	VOL INJECTED (mL)	PEAK AREA	MOLE METHANE (mol)	MOLE FRACTION (x_g)	PARTIAL PRESSURE
0.16	0.00025	23300	1.11814E-08	1.66622E-06	0.0016
0.16	0.00025	20600	1.11814E-08	1.66622E-06	0.0016
0.16	0.00025	21976	1.11814E-08	1.66622E-06	0.0016
1	0.0016	129220	7.15611E-08	1.06638E-05	0.01
1	0.0016	138030	7.15611E-08	1.06638E-05	0.01
1	0.0016	139870	7.15611E-08	1.06638E-05	0.01
2	0.0032	256090	1.43122E-07	2.13277E-05	0.02
2	0.0032	266990	1.43122E-07	2.13277E-05	0.02
2	0.0032	269250	1.43122E-07	2.13277E-05	0.02
3	0.0049	375760	2.19156E-07	3.2658E-05	0.03
3	0.0049	421210	2.19156E-07	3.2658E-05	0.03
3	0.0049	416340	2.19156E-07	3.2658E-05	0.03
4	0.0066	554440	2.9519E-07	4.39883E-05	0.04
4	0.0066	489670	2.9519E-07	4.39883E-05	0.04
4	0.0066	567370	2.9519E-07	4.39883E-05	0.04
6	0.0101	784720	4.51729E-07	6.73154E-05	0.06
6	0.0101	827330	4.51729E-07	6.73154E-05	0.06
6	0.0101	769410	4.51729E-07	6.73154E-05	0.06
8	0.01374	1081200	6.14531E-07	9.15757E-05	0.08
8	0.01374	1114100	6.14531E-07	9.15757E-05	0.08
8	0.01374	1165000	6.14531E-07	9.15757E-05	0.08



Temperature:	25 deg C
Molecular weight	16 g/mol
Headspace Volume (Vg)	4 ml
Liquid Volume (Vw)	39.8 ml
Henry's Constant	41300 unitless

$$C = MW\left[\frac{55.5}{H} + \frac{V_g}{V_w}\frac{1}{22.4}\frac{273}{(T+273)}\right]X_g$$

WELL SITE	REP #	PEAK AREA	[illegible]	[illegible]	[illegible]
MB	1	173810	0.01395	1.130	
	2	163310	0.01383	1.160	1.2
	3	175420	0.01398	1.141	
HP-13	1	198550	0.01470	1.283	
	2	200950	0.01487	1.297	1.3
	3	199040	0.01477	1.299	
27	1	167520	0.01253	1.093	
	2	154790	0.01184	1.015	1.1
	3	160812	0.01206	1.052	
HP-07	1	0	0.00000	0.070	0.0
HP-10	1	117050	0.00869	0.765	
	2	119050	0.00880	0.784	0.8
	3	119040	0.00880	0.784	
HP-09	1	50533	0.00434	0.379	
	2	51323	0.00439	0.383	0.4
	3	50800	0.00436	0.381	
28	1	124000	0.00953	0.831	
	2	125290	0.00957	0.835	0.8
	3	124592	0.00952	0.831	
HP-12	1	58600	0.00477	0.416	
	2	61720	0.00512	0.447	0.4
203	1	0	0.00000	0.070	0.0
17	1	27041	0.00275	0.240	
	2	18315	0.00200	0.182	0.2
	3	17883	0.00204	0.178	
HP-11	1	0	0.00000	0.070	0.0
SW2	1	0	0.00000	0.070	0.0
900	1	9377	0.00148	0.127	
	2	8723	0.00141	0.123	0.1
	3	8940	0.00143	0.125	
207	1	0	0.00000	0.070	0.0
HP-06	1	0	0.00000	0.070	0.0
27 (DUP)	1	137960	0.01048	0.913	
	2	147870	0.01115	0.973	0.9
	3	143740	0.01088	0.948	
26	1	0	0.00000	0.070	0.0
AH-17	1	185300	0.01239	1.080	
	2	180580	0.01207	1.108	1.1
	3	185570	0.01239	1.081	
AH-15	1	284110	0.01929	1.683	
	2	256170	0.01873	1.635	1.6
	3	248540	0.01820	1.588	
12	1	79953	0.00539	0.554	
	2	79974	0.00533	0.562	0.6
	3	82792	0.00560	0.575	
SW1	1	0	0.00000	0.070	0.0
13	1	0	0.00000	0.070	0.0
HP-05	1	0	0.00000	0.070	0.0
HP-08	1	12147	0.00186	0.144	
	2	10815	0.00169	0.165	0.2
	3	13795	0.00170	0.154	
14	1	48875	0.00402	0.351	
	2	49803	0.00407	0.355	0.4
	3	50220	0.00422	0.377	
5	1	133870	0.01017	0.888	
	2	142380	0.01084	0.948	0.9
	3	145750	0.01109	0.969	

Notes:

- Liquid Volume is avg from three measurements in grad cylinder
- Zero (0) Peak area results in 0.07 mg/L methane due to offset of Standard Curve
- This value has been entered as 0 in Average Conc. column

APPENDIX E:

Slug Test Data

PRESSURE TRANSDUCER CALIBRATION

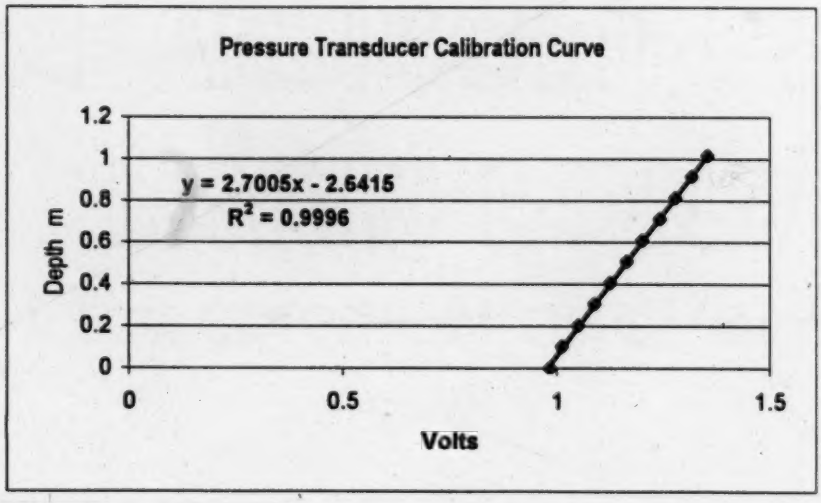
Depth inches	Depth m	volts
0	0	0.984
4	0.1016	1.013
8	0.2032	1.052
12	0.3048	1.09
16	0.4064	1.127
20	0.508	1.166
24	0.6096	1.202
28	0.7112	1.243
32	0.8128	1.279
36	0.9144	1.318
40	1.016	1.355

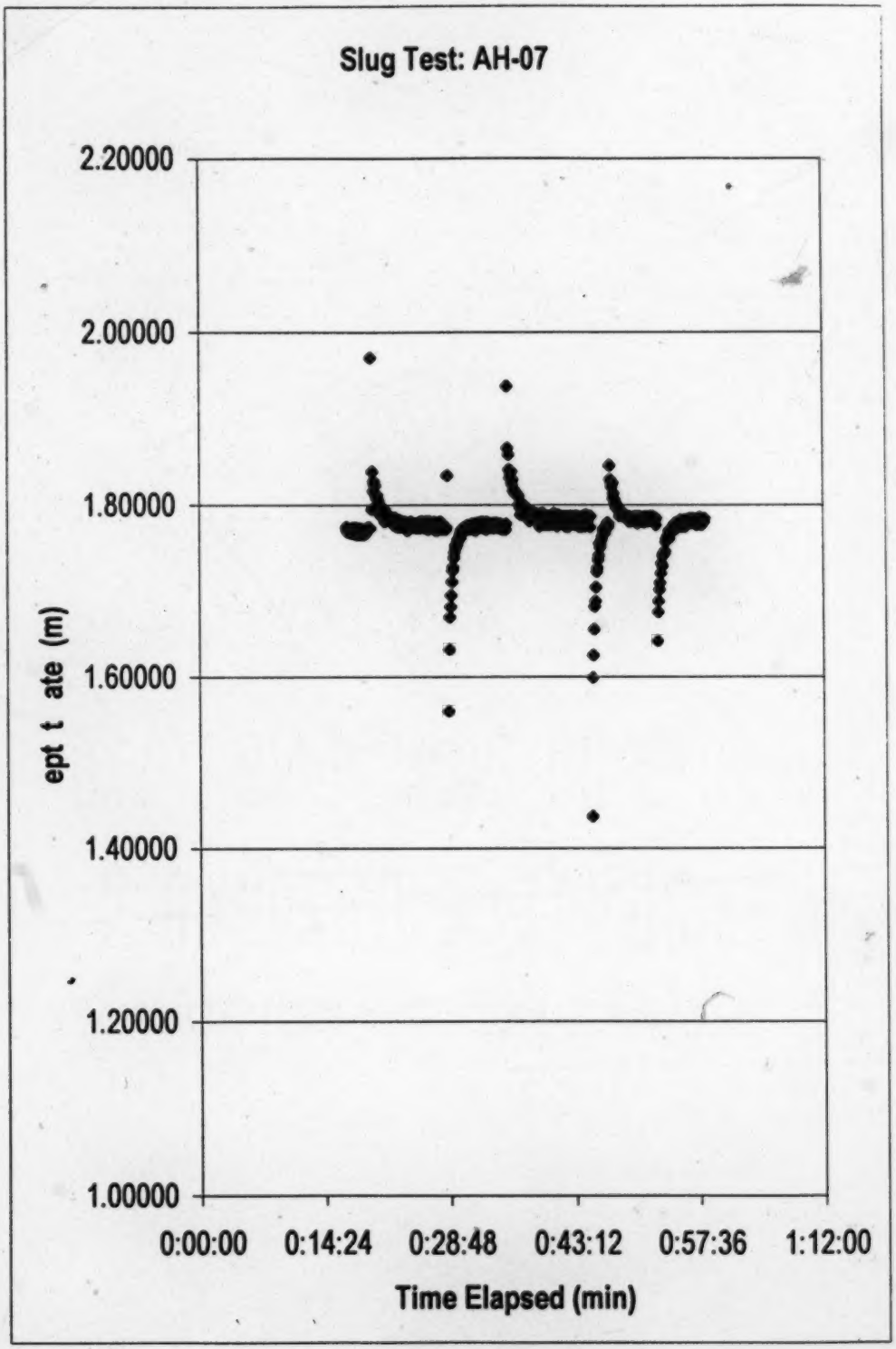
Downhole Temp

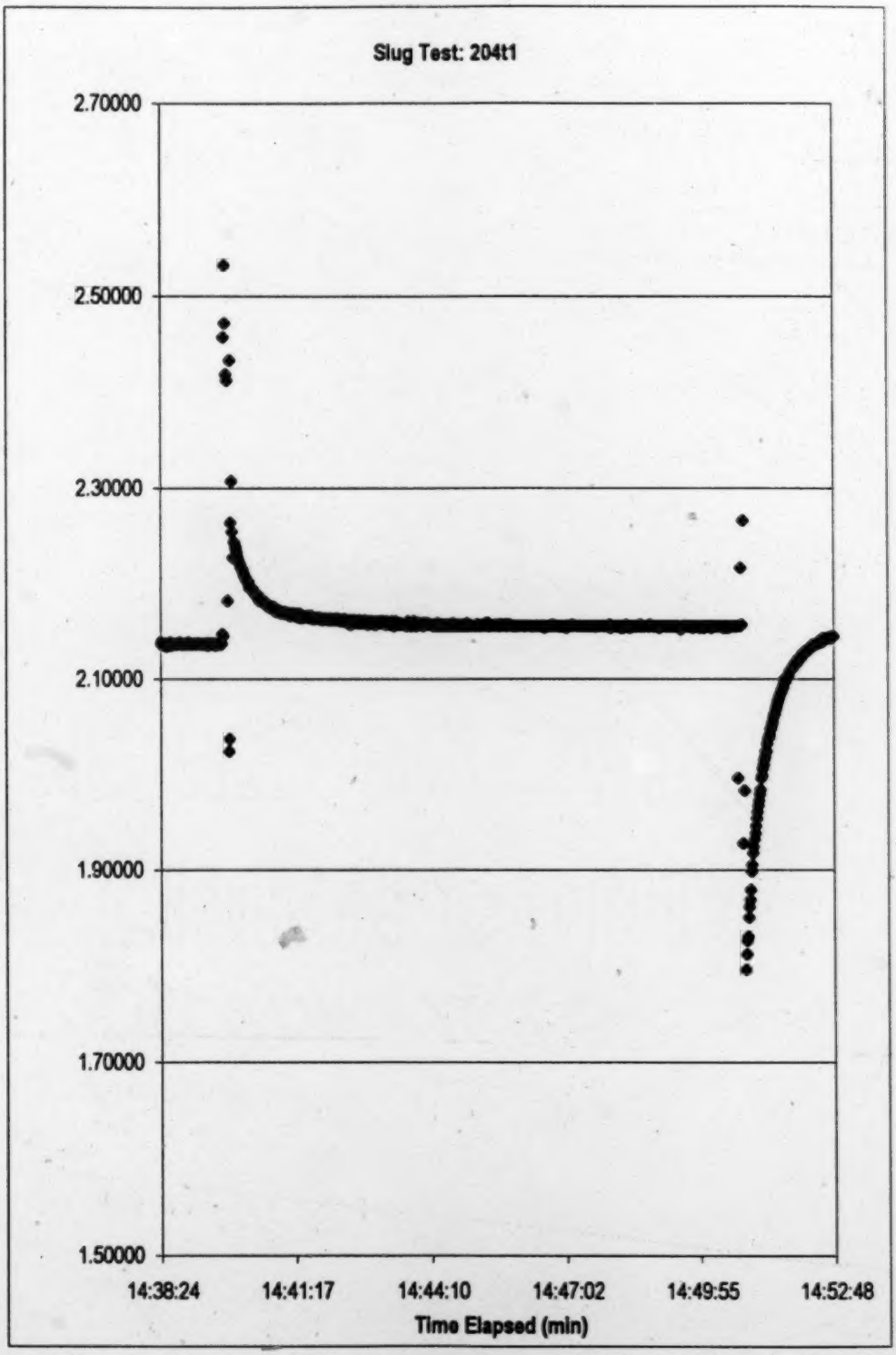
R-B = R1

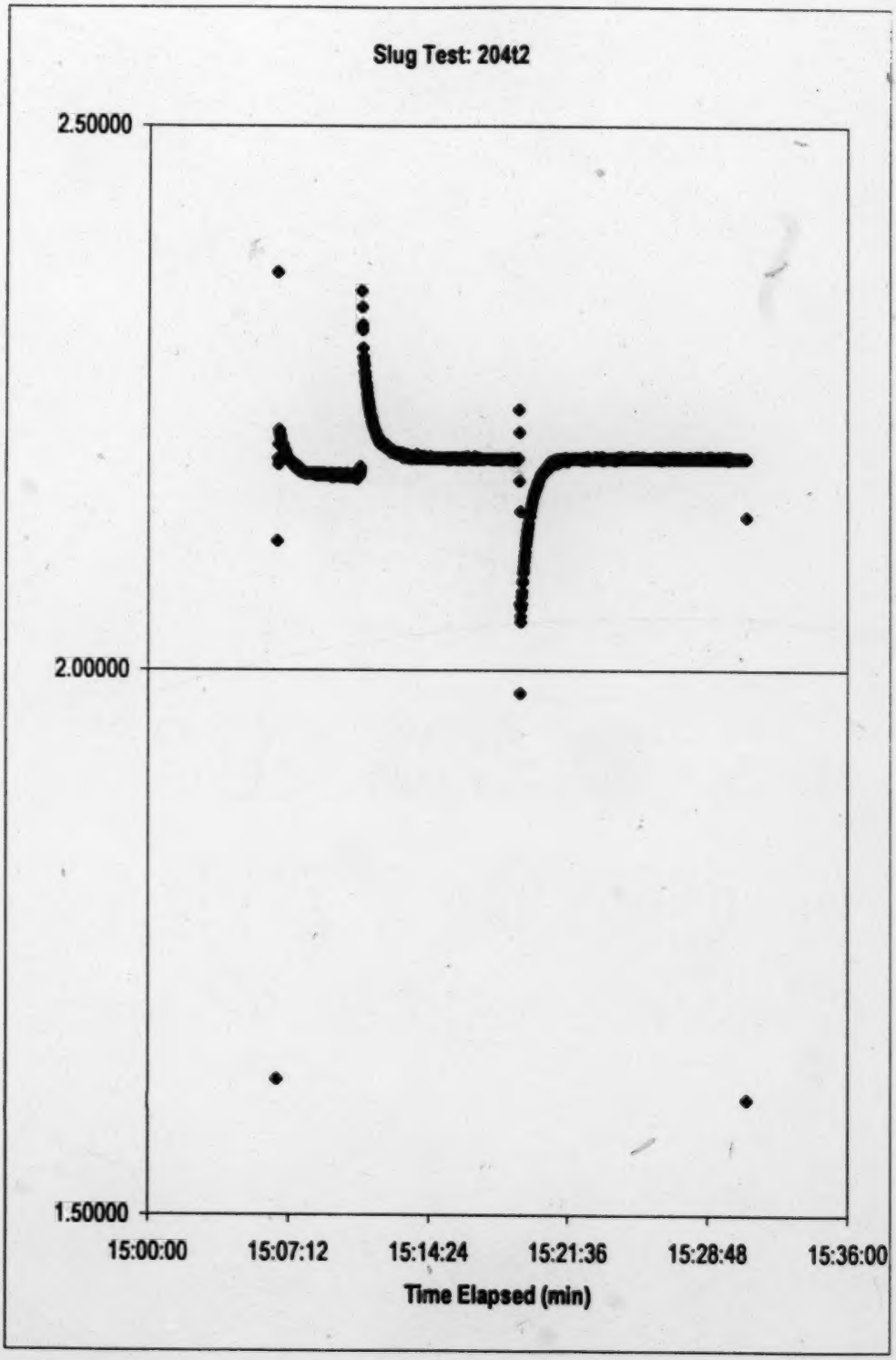
G-B=R2

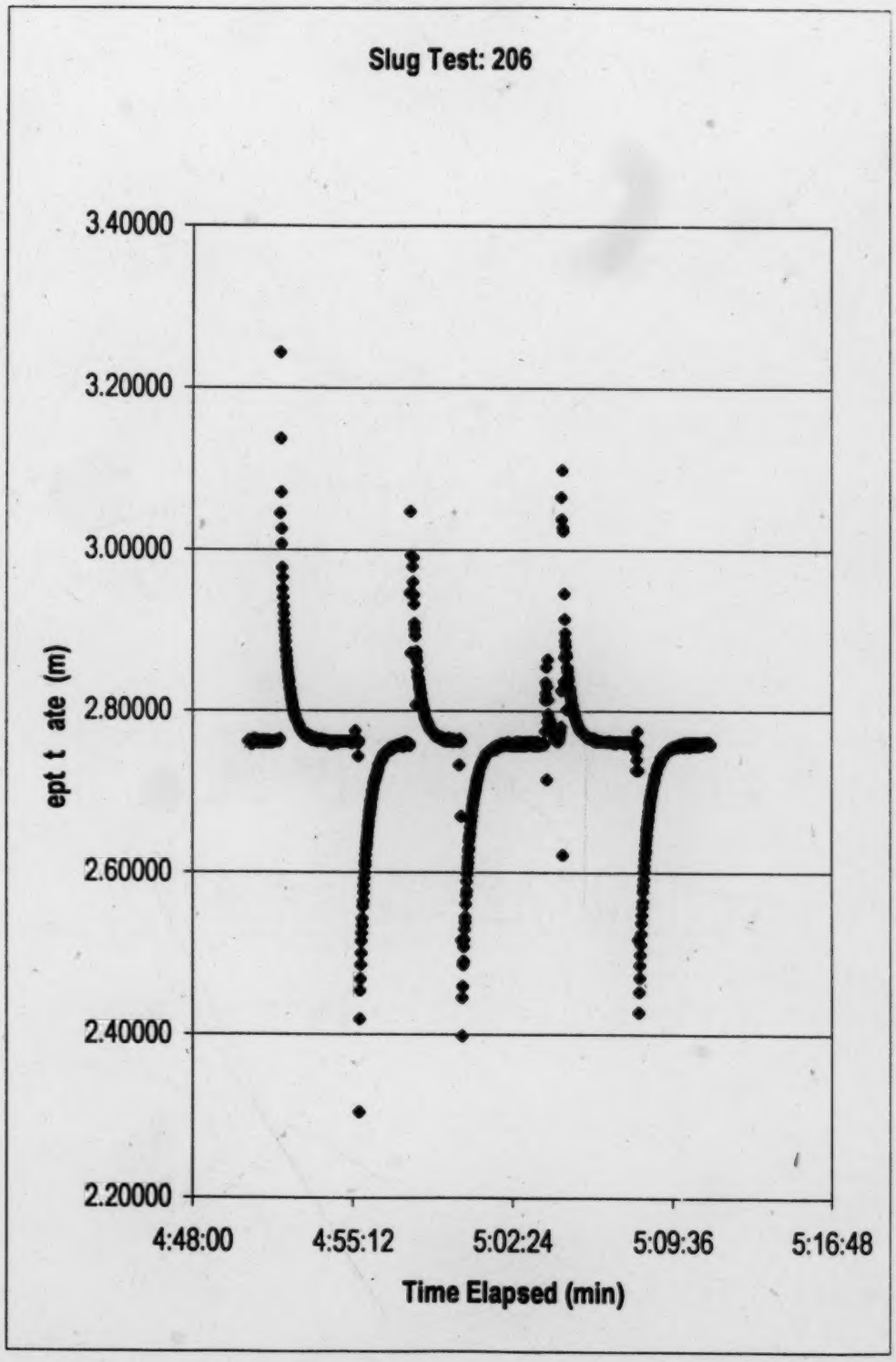
deg C = (R1-R2-100)/0.385




Slug Test: AH-07
2.20000
2.00000
1.80000
1.60000
1.40000
1.20000
1.00000
ept t ate (m)
0:00:00
0:14:24
0:28:48
0:43:12
0:57:36
1:12:00
Time Elapsed (min)


Slug Test: 204t1
2.70000
2.50000
2.30000
2.10000
1.90000
1.70000
1.50000
14:38:24
14:41:17
14:44:10
14:47:02
14:49:55
14:52:48
Time Elapsed (min)


Slug Test: 204t2
2.50000
2.00000
1.50000
15:00:00
15:07:12
15:14:24
15:21:36
15:28:48
15:36:00
Time Elapsed (min)


Slug Test: 206
3.40000
3.20000
3.00000
2.80000
2.60000
2.40000
2.20000
ept t ate (m)
4:48:00
4:55:12
5:02:24
5:09:36
5:16:48
Time Elapsed (min)

APPENDIX F:

University of Alberta Sieve Analysis

UNIVERSITY of ALBERTA
DEP'T. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY

SIEVE ANALYSIS

PROJECT Rate Study
SITE
SAMPLE Cold Lake
LOCATION AH-13 Near 27
HOLE DEPTH
TECHNICIAN DATE June 14/99

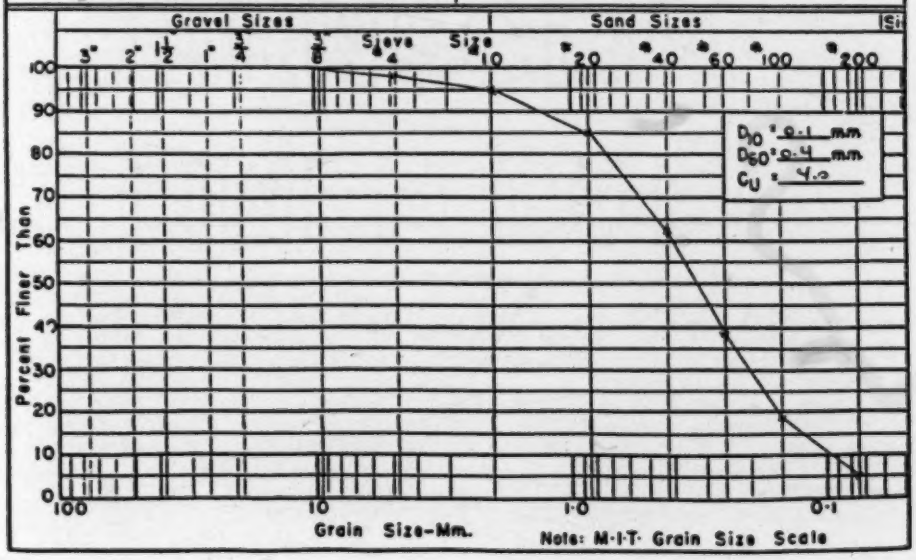
Total Dry Weight of Sample 258.59	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No.							
Wt. Dry + Tare							
Tare		3/8	19.10				
Wt. Dry		3/8	9.52		258.59	100	
	4	.185	4.76	3.88	254.71	98	
Passing	4						
Initial Dry Weight Passing No. 4							
Tare No.	10	.079	2.000	7.21	247.50	95	
Wt. Dry + Tare	20	.0331	.840	29.91	218.59	85	
Tare	40	.0165	.420	57.59	160.70	62	
Wt. Dry	60	.0097	.250	59.21	101.49	39.	
	100	.0059	.149	55.06	46.43	18	
	200	.0029	.074	33.04	13.39	5.1	
Passing	200			13.39			

Description of Sample
fine grain sand.

Time of Sieving 10 min

Method of Preparation
wash over # 200 Sieve

Remarks


Gravel Sizes
Sand Sizes
Sieve Size
3" 2" 1½ 1" ¾ ⅜ 4 10 20 40 60 100 200
100 90 80 70 60 50 40 30 20 10 0
Percent Finer Than
D10 = 0.1 mm
D60 = 0.4 mm
Cu = 4.0
100 10 1.0 0.1
Grain Size-Mm.
Note: M.I.T. Grain Size Scale

APPENDIX G:

Groundwater Elevations
and
Site Survey

SITE SURVEY

Hole I.D.	Northing	Easting	Elevation (m)
4	1590.103	6035.867	537.32
5	1368.835	6124.015	535.097
6	1214.115	6316.219	537.667
7	1274.128	6268.621	537.641
9	1262.791	6088.838	538.31
11	1339.262	6340.196	534.705
12	1181.719	6109.189	539.799
13	1203.204	6058.503	539.49
17	1149.058	6069.809	539.866
18	1126.272	6219.62	539.742
25	1296.559	6405.136	534.806
26	1314.492	6228.896	537.166
27	1236.719	6214.968	538.661
28	1199.504	6271.26	538.433
201	1108.525	6380.479	539.722
202	1155.715	6396.444	539.693
203	1255.264	6356.322	536.289
204	1267.334	6298.29	536.806
205	1292.868	6254.553	536.74
206	1280.019	6222.76	537.119
207	1398.872	6134.271	535.642
208	1409.679	6105.216	535.62
209	1476.137	6102.449	535.571
210	1285.313	6173.267	537.091
211	1184.081	6294.014	538.26
212	1213.665	6388.169	537.545
606	1040.489	6412.304	539.464
609	1100.292	6480.579	539.982
16A	1320.774	6322.992	535.777
16B	1320.174	6320.68	535.719
AH-1	866.887	6408.731	540.141
AH-16	1380.503	6348.13	533.191
AH-17	1375.018	6302.927	533.894
AH-18	1410.451	6347.62	532.754
AH-19	1375.075	6264.235	534.141
AH-2	1036.454	6056.311	539.574
AH-20	1163.704	6111.033	538.647
AH-3	1274.063	6018.17	537.763
AH-4	1335.945	6095.279	537.463
AH-5	1299.317	6126.092	537.511
AH-6	1239.613	6089.831	538.051
AH-7	1228.913	6175.698	538.7
AH-8	1230.697	6174.269	538.79
HP-10	1112.278	6121.842	539.243
HP-11	1112.143	6121.878	539.242
HP-12	1335.556	6098.749	537.303
HP-13	1236.667	6332.208	536.299
HP-14	1375.086	6297.49	533.889
HP-21	1116.379	6379.617	539.117
HP-22	1155.887	6239.009	538.527
HP-23	1315.361	6326.141	534.835
HP-24	1289.408	6311.474	535.991
HP-25	1236.657	6281.773	536.547
HP-26	1275.728	6266.436	536.723
HP-5	1064.741	6034.521	540.019
HP-8	1143.426	6181.826	538.768
HP-9	1165.531	6139.434	538.385
N (12)	1157.207	6114.683	539.597
O (14)	1112.958	6090.334	540.208
Outfall	1250.515	6300.707	534.944

GROUNDWATER ELEVATIONS

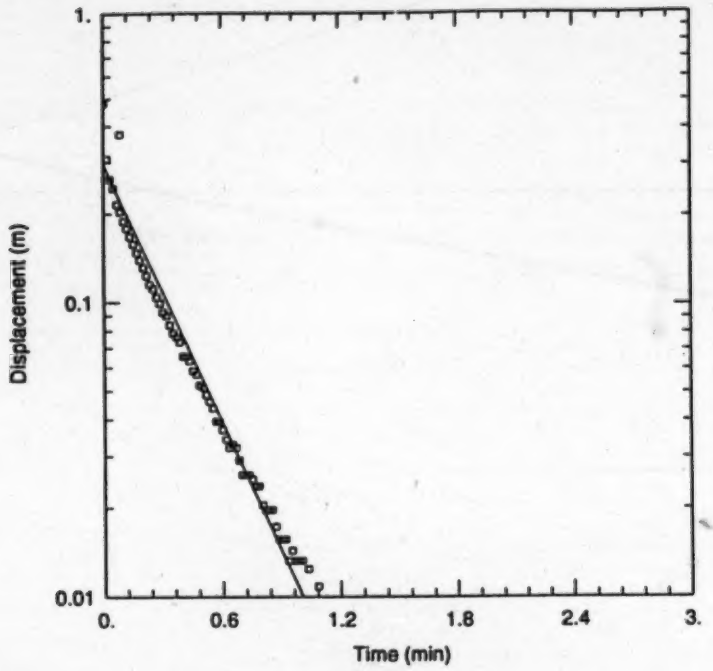
Hole I.D.	Northing	Easting	June 15,1998 Water Elev. (m)	Aug 6,1998 Water Elev. (m)	Oct 27,1998 Water Elev. (m)
4	1590.103	6035.867	535.081	534.151	
5	1368.835	6124.015	532.972		
6	1214.115	6316.219	535.214	535.432	535.287
7	1274.128	6268.621	534.801	534.968	534.881
9	1262.791	6088.838		536.358	535.996
11	1339.262	6340.196		527.147	
12	1181.719	6109.189	536.589		536.475
13	1203.204	6058.503	536.803	536.824	536.637
16A	1320.774	6322.992			
16B	1320.174	6320.68		533.733	532.92
17	1149.058	6069.809	537.196		537.01
18	1126.272	6219.62	536.202	536.557	
25	1296.559	6405.136			533.713
26	1314.492	6228.896	535.144	535.291	535.137
27	1236.719	6214.966	535.62	535.889	535.803
28	1199.504	6271.26	535.636	535.873	
201	1108.526	6360.479	539.722	536.392	536.252
202	1155.715	6396.444	536.005	536.252	536.083
203	1255.264	6356.322		534.957	534.972
204	1267.334	6298.29		534.786	534.794
205	1292.868	6254.553	534.993	535.117	534.013
206	1280.019	6222.76	535.784	535.605	535.365
207	1398.872	6134.271	533.657	533.751	533.49
208	1409.679	6105.216	533.809	533.849	533.626
209	1476.137	6102.449	533.269	533.277	
210	1285.313	6173.267		535.95	535.603
211	1184.081	6294.014	535.721	535.989	535.792
212	1213.665	6368.169		535.411	535.31
608	1040.489	6412.304		536.945	536.678
609	1100.292	6480.579		537.117	536.966
AH-02	1036.454	6056.311			
AH-03	1274.063	6018.17			
AH-04	1335.945	6095.279			
AH-05	1299.317	6126.092			
AH-06	1239.613	6089.831			
AH-07	1228.913	6175.698			535.926
AH-08	1230.697	6174.269			
AH-16	1360.503	6348.13			
AH-17	1375.018	6302.927			
AH-18	1410.451	6347.62			
AH-19	1375.075	6264.235			
AH-20	1163.704	6111.033			
HP-5	1064.741	6034.521			
HP-8	1143.426	6181.826			
HP-9	1165.531	6139.434			
HP-10	1112.278	6121.842			
HP-11	1112.143	6121.878			
HP-12	1335.556	6098.749			
HP-13	1236.667	6332.208			
HP-14	1375.066	6297.49			
HP-15					
HP-16	784.289	6281.187		534.762	
HP-17	913.106	6433.639			534.565
HP-18	957.21	6410.506			529.641
HP-19	968.893	6391.657			534.685
HP-20					
HP-21	1116.379	6379.817			
HP-22	1155.887	6239.008			536.387
HP-23	1315.361	6326.141			534.255
HP-24	1289.408	6311.474			534.671
HP-25	1236.657	6281.773			535.357
HP-26	1275.728	6266.435			535.048
N (12)	1157.207	6114.683	536.892	537.069	
O (14)	1112.958	6090.334	537.173	537.339	537.137
Outfall	1250.515	6300.707			

MAX	539.722	537.117	537.01
MIN	532.972	527.147	532.92
MAX HEAD LOSS	6.75	9.97	4.09

APPENDIX H:

Aqtesolve Analysis
and
University of Alberta Permeameter Tests

SENSITIVITY ANALYSIS FOR CASING AND WELL RADIUS



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\N206AI.AQT
Date: 05/10/99 Time: 15:10:03

AQUIFER DATA

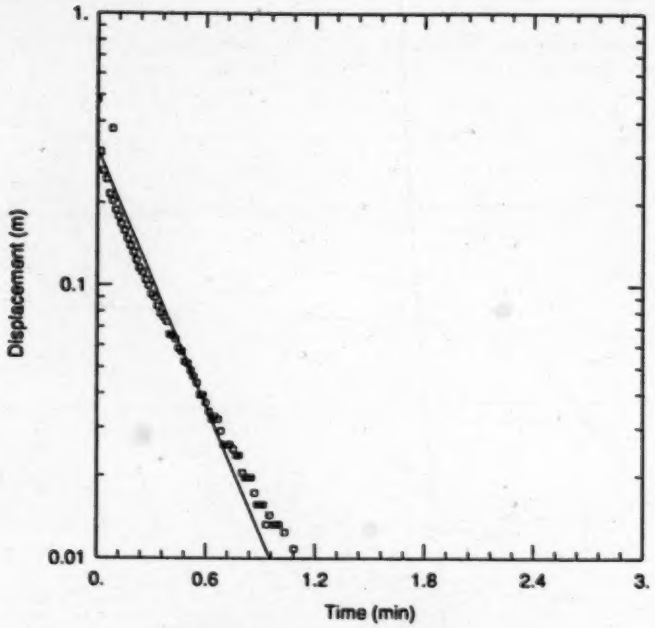
Saturated Thickness: 1.43 m
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

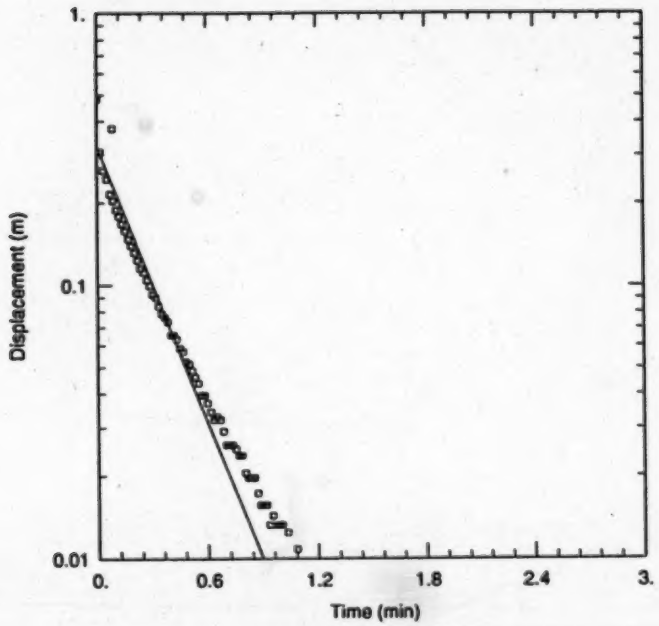
Initial Displacement: 0.481 m
Water Column Height: 1.43 m
Casing Radius: 0.0215 m
Wellbore Radius: 0.12 m
Screen Length: 3.2 m
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Unconfined
K = 0.006191 m/min
Solution Method: Bouwer-Rice
y0 = 0.2958 m



WELL TEST ANALYSIS	
Data Set: G:\USERS\MULLICK\N206AII.AQT	
Date: 05/10/99	Time: 15:12:19
AQUIFER DATA	
Saturated Thickness: 1.43 m	Anisotropy Ratio (Kz/Kr): 1.
WELL DATA	
Initial Displacement: 0.481 m	Water Column Height: 1.43 m
Casing Radius: 0.0215 m	Wellbore Radius: 0.04 m
Screen Length: 3.2 m	Gravel Pack Porosity: 0.4
SOLUTION	
Aquifer Model: Unconfined	K = 0.001469 m/min
Solution Method: Bouwer-Rice	y0 = 0.3148 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\N206AIII.AQT
Date: 05/10/99 Time: 15:16:25

AQUIFER DATA

Saturated Thickness: 1.43 m
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

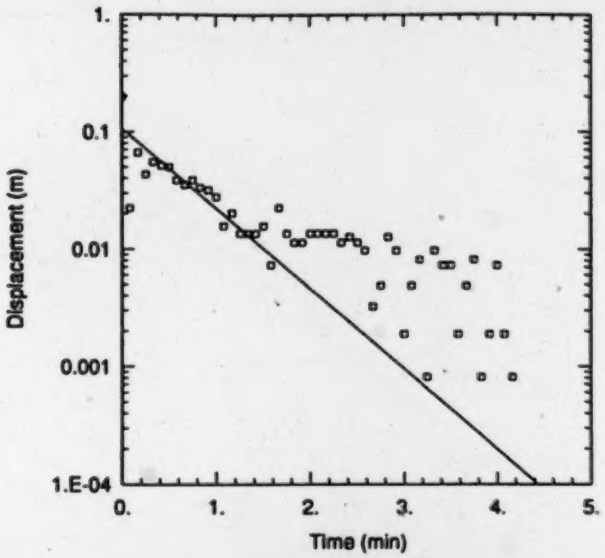
Initial Displacement: 0.481 m
Casing Radius: 0.04 m
Screen Length: 3.2 m
Water Column Height: 1.43 m
Wellbore Radius: 0.12 m
Gravel Pack Porosity: 0.4

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.007936 m/min
y0 = 0.322 m

K (m/s) for well 206

	n = 0.4			n = 0.30		
	r_c = 2 cm r_w = 12cm	r_c = 2 cm r_w = 4cm	r_c = 4 cm r_w = 12cm	r_c = 2.5 cm r_w = 11cm	Average	Std. Deviation
206a	1.0E-04	2.4E-05	1.3E-04	6.4E-05	8.1E-05	4.7E-05
206b	8.3E-05	1.7E-05	9.4E-05	5.7E-05	6.3E-05	3.4E-05
206c	9.5E-05	2.0E-05	1.1E-04	7.2E-05	7.4E-05	3.9E-05
206d	8.7E-05	1.9E-05	9.8E-05	6.1E-05	6.6E-05	3.5E-05
206e	1.2E-04	2.5E-05	1.4E-04	6.5E-05	8.7E-05	5.2E-05
206f	8.8E-05	1.9E-05	9.9E-05	6.2E-05	6.7E-05	3.6E-05



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\NAH7A.AQT
Date: 07/06/99 Time: 21:15:48

AQUIFER DATA

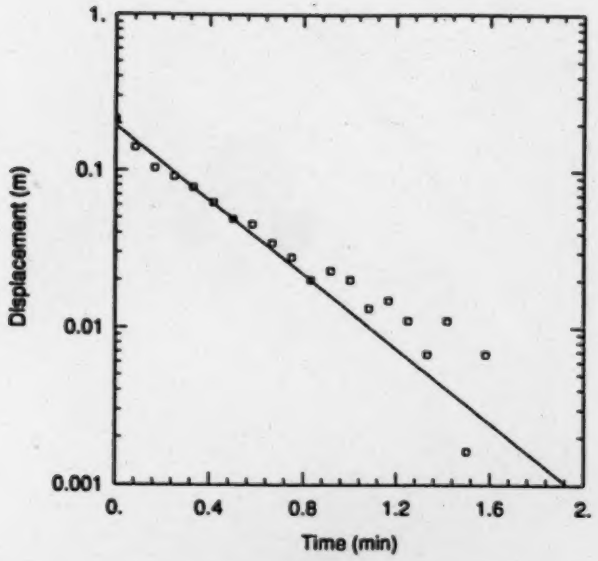
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 0.1974 m
Water Column Height: 1. m
Casing Radius: 0.025 m
Wellbore Radius: 0.08 m
Screen Length: 0.76 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
K = 0.004293 m/min
Solution Method: Bouwer-Rice
y0 = 0.1061 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\NAH7B.AQT
Date: 07/06/99 Time: 21:15:57

AQUIFER DATA

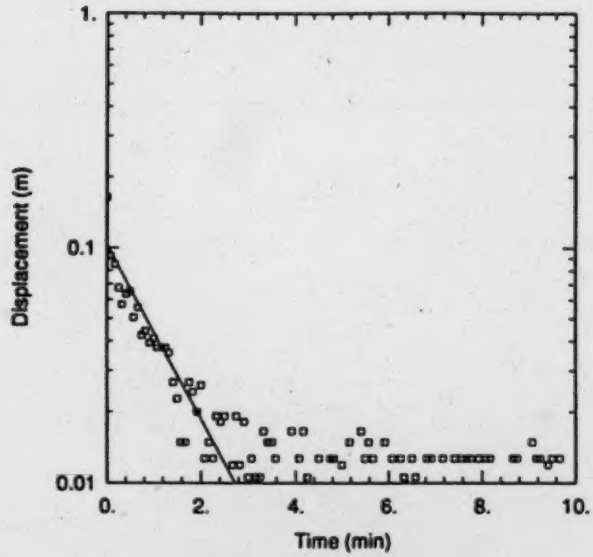
Saturated Thickness: 1. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 0.2128 m Water Column Height: 1. m
Casing Radius: 0.025 m Wellbore Radius: 0.08 m
Screen Length: 0.76 m Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined K = 0.00746 m/min
Solution Method: Bouwer-Rice y0 = 0.1926 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\NAH7C.AQT
Date: 07/06/99 Time: 21:16:06

AQUIFER DATA

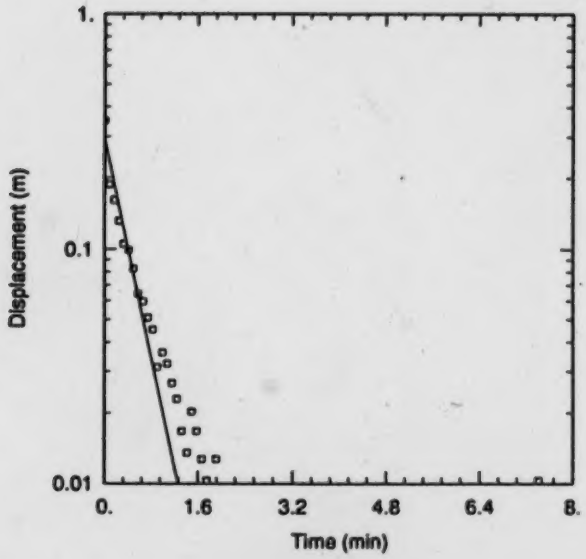
Saturated Thickness: 1. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 0.1639 m Water Column Height: 1. m
Casing Radius: 0.025 m Wellbore Radius: 0.08 m
Screen Length: 0.76 m Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined K = 0.002334 m/min
Solution Method: Bouwer-Rice y0 = 0.1028 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\NAH7D.AQT
Date: 07/06/99 Time: 21:16:18

AQUIFER DATA

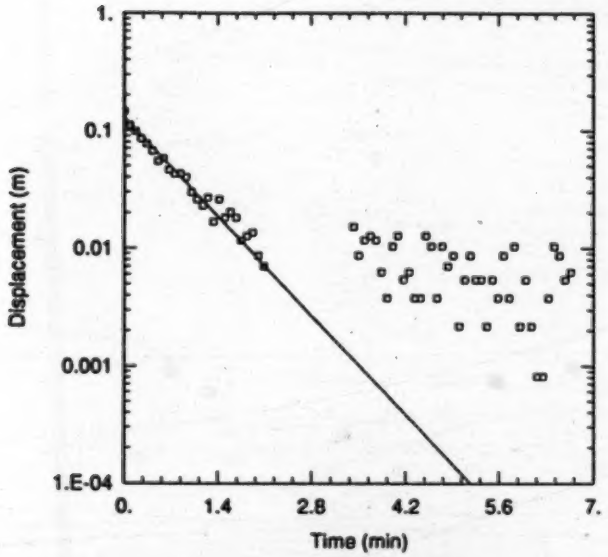
Saturated Thickness: 1. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 0.3489 m Water Column Height: 1. m
Casing Radius: 0.025 m Wellbore Radius: 0.08 m
Screen Length: 0.76 m Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined K = 0.007254 m/min
Solution Method: Bouwer-Rice y0 = 0.2916 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\NAH7E.AQT
Date: 07/06/99 Time: 21:16:28

AQUIFER DATA

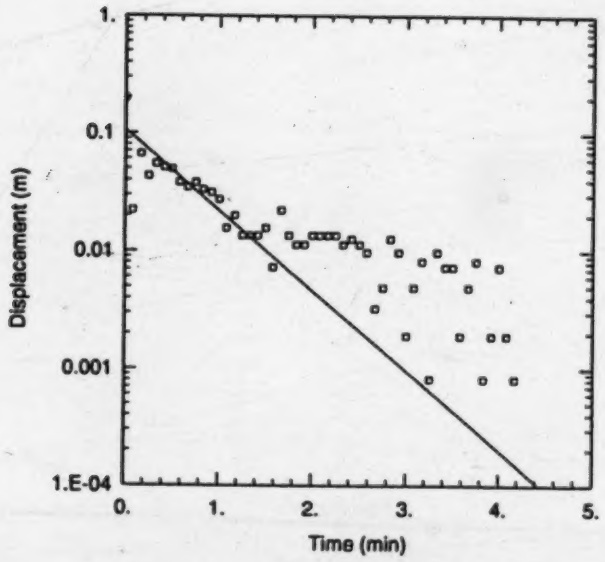
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Initial Displacement: 0.145 m
Water Column Height: 1. m
Casing Radius: 0.025 m
Wellbore Radius: 0.08 m
Screen Length: 0.76 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
K = 0.003783 m/min
Solution Method: Bouwer-Rice
y0 = 0.1282 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\3NAH7A.AQT
Date: 07/06/99 Time: 21:15:34

AQUIFER DATA

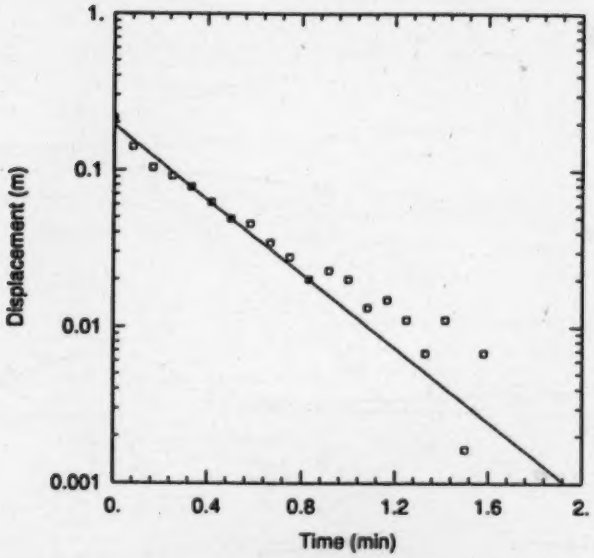
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 0.33

WELL DATA

Initial Displacement: 0.1974 m
Water Column Height: 1. m
Casing Radius: 0.025 m
Wellbore Radius: 0.08 m
Screen Length: 0.76 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.005403 m/min
y0 = 0.1061 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\3NAH7B.AQT
Date: 07/06/99 Time: 21:15:30

AQUIFER DATA

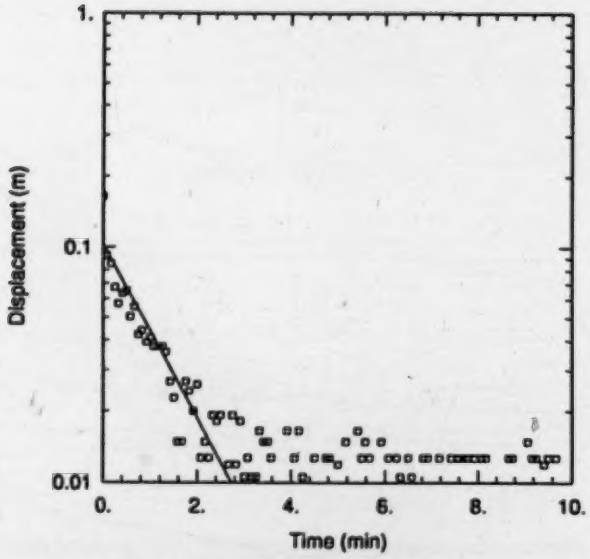
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 0.33

WELL DATA

Initial Displacement: 0.2128 m
Casing Radius: 0.025 m
Screen Length: 0.76 m
Water Column Height: 1. m
Wellbore Radius: 0.08 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.009389 m/min
y0 = 0.1926 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\3NAH7C.AQT
Date: 07/06/99 Time: 21:15:25

AQUIFER DATA

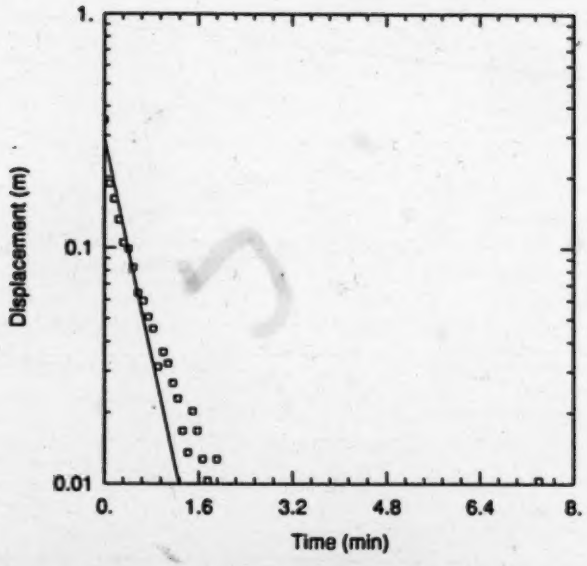
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 0.33

WELL DATA

Initial Displacement: 0.1639 m
Casing Radius: 0.025 m
Screen Length: 0.76 m
Water Column Height: 1. m
Wellbore Radius: 0.08 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.002937 m/min
y0 = 0.1028 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\3NAH7D.AQT
Date: 07/06/99 Time: 21:15:21

AQUIFER DATA

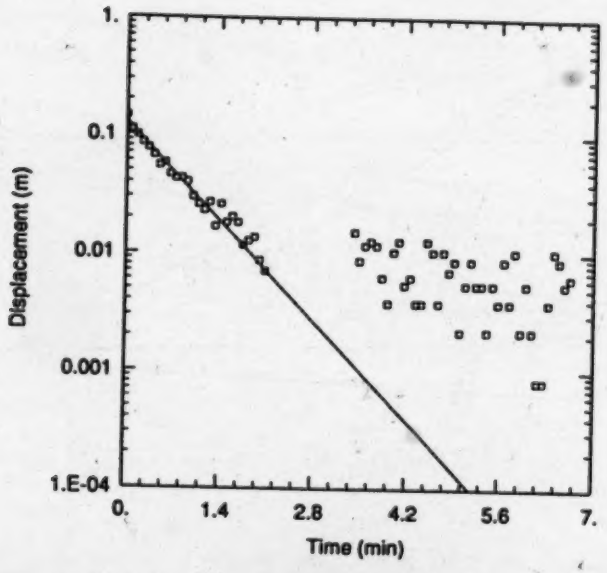
Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 0.33

WELL DATA

Initial Displacement: 0.3489 m
Water Column Height: 1. m
Casing Radius: 0.025 m
Wellbore Radius: 0.08 m
Screen Length: 0.76 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
K = 0.009129 m/min
Solution Method: Bouwer-Rice
y0 = 0.2916 m



WELL TEST ANALYSIS

Data Set: G:\USERS\MULLICK\3NAH7E.AQT
Date: 07/06/99 Time: 21:15:15

AQUIFER DATA

Saturated Thickness: 1. m
Anisotropy Ratio (Kz/Kr): 0.33

WELL DATA

Initial Displacement: 0.145 m
Casing Radius: 0.025 m
Screen Length: 0.76 m
Water Column Height: 1. m
Wellbore Radius: 0.08 m
Gravel Pack Porosity: 0.3

SOLUTION

Aquifer Model: Unconfined
Solution Method: Bouwer-Rice
K = 0.004761 m/min
y0 = 0.1282 m

Summary of Hydraulic Conductivies When Varying the Anisotropic Ratio

Hydraulic Conductivity (m/s)		
WELL	Kz/Kr = 1	Kz/Kr = 0.3
204a	4.8E-05	4.8E-05
204b	6.5E-05	6.5E-05
204c	5.0E-05	5.0E-05
204aa	4.4E-05	5.3E-05
206a	9.3E-05	9.3E-05
206b	6.5E-05	6.5E-05
206c	7.2E-05	7.2E-05
206d	6.1E-05	6.1E-05
206e	8.9E-05	8.9E-05
206f	6.2E-05	6.2E-05
AH7a	7.2E-05	9.0E-05
AH7b	1.2E-04	1.6E-04
AH7c	3.9E-05	4.9E-05
AH7d	1.2E-04	1.5E-04
AH7e	6.3E-05	7.9E-05
Average	7.1E-05	7.9E-05

COEFFICIENT OF PERMEABILITY (Constant Head, Falling Head) Data Sheet 11. 12

Project Rate Study Job No.

Location of Project Cold Lake AH-19 Near 27

Description of Soil

Tested by Date of Testing June 14/88

Sample Dimensions: Diam. 7.65 cm; Area 46.0 cm²

Mass soil + pan Init. g Ht. 17.8 cm

Mass soil + pan Final g Vol. 818.5 cm³

Mass of Sample 1311.1 g Density, ρ 1.602 g/cm³

Constant Head

h = 40.7 cm

Test data *Test data used*

Test No.	t, s	Q, cm³	T, °C	Test No.	t, s	Q, cm³	T, °C
1	60	127.35					
2	60	127.38					
3	60	126.69					
4	60	126.62					
				Average[a]	127.01		

$k_T = \frac{QL}{hAt}$ = _____

= 0.0201 cm/s

$\alpha = \eta_T/\eta_{20}$ = 0.953

$k_{20} = \alpha k_T$ = 0.0192 cm/s

Falling Head

Standpipe = [burette, other (specify)] _____ Area standpipe, a = _____ cm²

Test data[b] *Test data used*

Test no	h_1, cm	h_2, cm	t, s	Q_{av}, cm³	Q_{av}, cm³	T, °C	Test no.	h_1, cm	h_2, cm	t, s	T, °C
1											
2											
3											
4											
							Average				

$\alpha = \eta_T/\eta_{20}$ = _____

$k_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$ = _____ = _____ cm/s

$k_{20} = \alpha k_T$ = _____ = _____ cm/s

[a] Use averaged values only if there is a small difference in test temperature, say, 1–2°C.
[b] Simplify by using the same h_1 and h_2 each time, so you can average k.

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COEFFICIENT OF PERMEABILITY (Constant Head, Falling Head) Data Sheet 11, 12

Project Rate Study. Job No. _____

Location of Project Cold Lake BH-19 Rear 37

Description of Soil _____

Tested by _____ Date of Testing June 14/99

Sample Dimensions: Diam. 7.65 cm; Area 46.0 cm² Dia. 7.65 cm

Mass soil + pan Init. _____ g Ht. 17.5, 17.5, 17.5 cm

Mass soil + pan Final _____ g Vol. 813.15 cm³

Mass of Sample 1311.4 g Density, ρ 1.607 g/cm³

↳ DRY MASS OF SAMPLE OVER VOLUME OF SAMPLE.

Constant Head

h = 54.1 cm

Test data *Test data used*

Test No.	t, s	Q, cm³	T, °C	Test No.	t, s	Q, cm³	T, °C
1	60	166.35	22°C				
2	70	192.99	22°C				
3	60	167.33	22°C				
4	60	165.60	22°C				
				Average[a]	166.39		

$k_T = \frac{QL}{Aht}$ = _____

= 0.0198 cm/s

$\alpha = \eta_T/\eta_{20}$ = 0.9532

$k_{20} = \alpha k_T$ = 0.01887 cm/s

Falling Head

Standpipe = [burette, other (specify)] _____ Area standpipe, a = _____ cm²

Test data[b] *Test data used*

Test no.	h_1, cm	h_2, cm	t, s	Q_w, cm³	Q_{soil}, cm³	T, °C	Test no.	h_1, cm	h_2, cm	t, s	T, °C
1											
2											
3											
4											
							Average				

$\alpha = \eta_T/\eta_{20}$ = _____

$k_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$ = _____ = _____ cm/s

$k_{20} = \alpha k_T$ = _____ = _____ cm/s

[a]Use averaged values only if there is a small difference in test temperature, say, 1–2°C.
[b]Simplify by using the same h_1 and h_2 each time, so you can average k.

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COEFFICIENT OF PERMEABILITY (Constant Head, Falling Head) Data Sheet 11, 12

Project Rate Study Job No. _____

Location of Project Cold Lake AH - 19 Near: 27

Description of Soil _____

Tested by _____ Date of Testing June 14 / 99

Sample Dimensions: Diam. 7.65 cm; Area 46.0 cm²

Mass soil + pan Init. _____ g Ht 17.8 cm

Mass soil + pan Final _____ g Vol. 818.15 cm³

Mass of Sample 1311.9 g Density, ρ 1.602 g/cm³

Constant Head

h = 665 cm

Test data *Test data used*

Test No.	t, s	Q, cm³	T, °C	Test No.	t, s	Q, cm³	T, °C
1	60	198.42	22°C				
2	60	198.79	22°C				
3	60	199.40	22°C				
4	60	197.84	22°C				
				Average[a]	198.6		

$k_T = \frac{Qt}{Aht}$ = _____

= 0.0192 cm/s

$\alpha = \eta_T/\eta_{20}$ = 0.953

$k_{20} = \alpha k_T$ = 0.0183 cm/s

Falling Head

Standpipe = [burette, other (specify)] _____ Area standpipe, a = _____ cm²

Test data[b] *Test data used*

Test no.	h_1, cm	h_2, cm	t, s	Q_{av}, cm³	Q_{av}, cm³	T, °C	Test no.	h_1, cm	h_2, cm	t, s	T, °C
1											
2											
3											
4											
							Average				

$\alpha = \eta_T/\eta_{20}$ = _____

$k_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$ = _____ = _____ cm/s

$k_{20} = \alpha k_T$ = _____ = _____ cm/s

[a]Use averaged values only if there is a small difference in test temperature, say, 1–2°C.
[b]Simplify by using the same h_1 and h_2 each time, so you can average it.

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APPENDIX I:

Geochemistry and Contaminant Summary

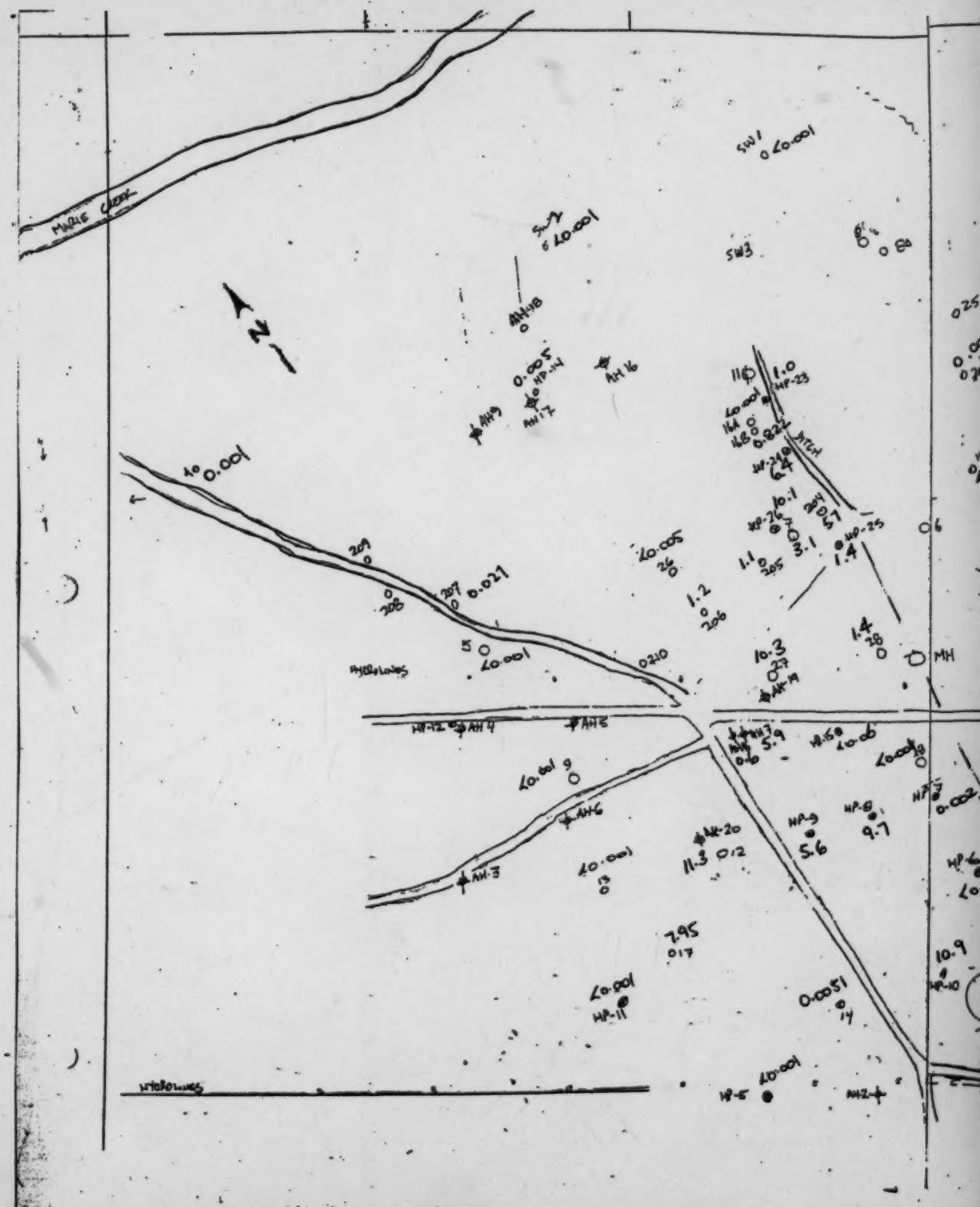
LABORATORY ANALYSIS OF GROUNDWATER SAMPLES

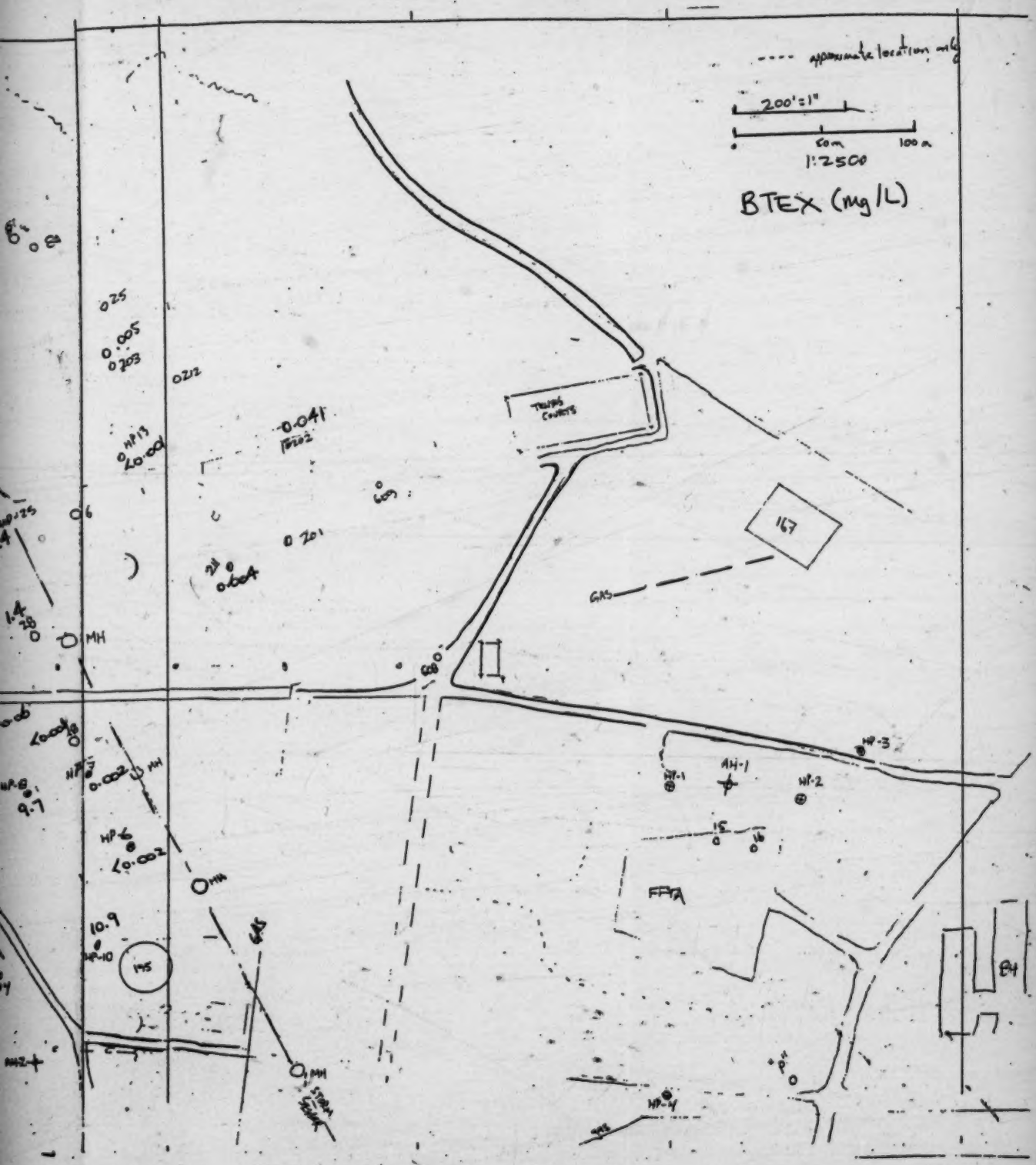
		WATER NUTRIENTS		WATER CHEMISTRY				NON-HALOGENTATED AROMATICS					VOLATILE ORGANIC COMPOUNDS			
WELL SITE	DATE	$NO_3 + NO_2$	SO_4	S^{2-}	TOC	CH_4	Fe^{2+}	Benzene	Toluene	Ethylbenzene	Xylenes	Σ BTEX	1,1,1-TCA	1,1-DCA	DCBs	VC
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(mg/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)
4	17-Jan-96							< 1.0	1	< 1.0	< 1.0	0.001	1	< 1.0	< 1.0	< 2.0
5	14-Aug-96	< 0.05	12.3	< 0.002	11		0.8	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
7	16-Aug-96							930	950	25	1540	3.115	< 1.0	35	67	< 10.0
9	16-Aug-96	0.1	0.8	0.002	8		0.4	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
12	16-Aug-96	< 0.2	< 0.5	< 0.002	67		128	4500	4500	350	7000	11.3	1300	55	98	< 2.0
13	15-Aug-96	0.06	23.7	< 0.002	11		< 0.1	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
14	7-Aug-96	< 0.05	< 0.5	0.023	25		44.1	< 0.1	1.1	0.2	3.8	0.0051	0.5	0.1	< 0.1	< 0.2
17	16-Jan-96							780	4100	290	2800	7.95	940	53	28	< 2
17	16-Aug-96	< 0.2	8.3	< 0.002	259		84.2	1700	5700	330	3700	11.43	2900	< 80.0	61	< 2.0
18	16-Jan-96							< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 1.0	< 1.0	< 2.0
26	16-Aug-96	< 0.05	26.6	< 0.002	10		< 0.1	< 1.0	< 4.0	< 1.0	< 5.0	< 0.005	< 3.0	1	< 3.0	< 2.0
27	17-Jan-96							1400	4500	850	3550	10.3	10000	150	54	4
28	16-Jan-96							3	40	41	1300	1.384	42	34	48	< 2
28	16-Aug-96	< 0.2	4	< 0.002	44		107	< 1.0	27	17	810	0.894	84	25	53	< 2.0
201	13-Aug-96							< 270	9200	2400	15100	26.7	< 270	< 540	< 270	< 540
202	17-Jan-96							1	14	3	23	0.041	2	< 2.0	< 1.0	< 2.0
203	8-Aug-96	0.83	29.8	0.003	8		1.8	< 1.0	< 1.0	< 1.0	5	0.005	< 1.0	< 2.0	< 1.0	< 2.0
204	3-Oct-96	< 0.2	13.9	0.002			202	19	2500	90	3100	5.709	8600	< 2.0	96	< 2.0
205	16-Jan-96							98	180	9	860	1.147	290	420	53	< 2
Duplicate 205	16-Jan-96							98	180	7	817	1.102	300	430	52	< 2
206	3-Oct-96	< 0.2	0.8	< 0.002			98.7	130	200	15	900	1.245	< 2.0	< 2.0	71	2
207	8-Aug-96	< 0.005	29.7	< 0.002	10		0.9	2	13	1	11	0.027	< 1.0	< 1.0	< 1.0	< 2.0
Duplicate 207	8-Aug-96	< 0.005	28.4	< 0.002	9		1	2.4	13	0.8	14	0.0303	< 1.0	< 1.0	< 1.0	< 2.0
211	16-Jan-96							< 1.0	2	< 1.0	2	0.004	< 1.0	< 1.0	< 1.0	< 2.0
998	8-Aug-96	0.06	1.8	< 0.002	7		0.1	< 1.0	< 1.0	< 1.0	7	0.007	< 1.0	< 2.0	< 1.0	< 2.0
199	16-Jan-96							< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 1.0	< 1.0	< 2.0
199	8-Aug-96	< 0.05	0.8	< 0.002	28		25.7	86	210	< 10	529	0.822	< 10	280	24	< 100
AH-97	3-Oct-96	< 0.2	25	0.003			217	1300	680	43	3900	5.923	3200	120	199	< 2.0
AH-98	3-Oct-96	< 0.05	21.8	< 0.002			9	14	29	< 2.0	140	0.003	29	< 2.0	36	< 2.0
Drainage Ditch	16-Jan-96							< 1.0	2	< 1.0	12	0.014	< 1.0	< 2.0	< 1.0	< 2.0
HP-01	12-Aug-96				9											
HP-04	13-Aug-96	< 0.05	11.1	< 0.002	4		66									
HP-05	13-Aug-96	10.7	8.4	< 0.002	36		< 0.1	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
HP-06	14-Aug-96						< 0.1	< 1.0	< 1.0	< 1.0	< 1.0	< 0.002	< 1.0	< 2.0	< 1.0	< 2.0
HP-07	14-Aug-96	1.56	38.1	< 0.002	27		< 0.1	< 1.0	2	< 1.0	< 1.0	0.002	< 1.0	< 2.0	< 1.0	< 2.0
HP-08	14-Aug-96	< 0.2	10.1	0.011	22		81.8	47	4000	180	5600	9.727	3900	140	122	< 2.0
Duplicate HP-08	14-Aug-96	< 0.2	9.9	0.011	21		80.2	45	3900	180	5700	9.835	3850	135	120	< 2.0
HP-09	14-Aug-96	< 0.2	4.9	< 0.002	32		498	210	1600	< 10	3800	5.61	2700	< 20	< 40	< 20
HP-10	14-Aug-96	< 0.05	3.7	0.023	25		119	< 1.0	35	41	10900	10.876	30	< 2.0	43	< 2.0
HP-11	14-Aug-96	1.02	3.9	< 0.002	18		< 0.1	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
HP-12	14-Aug-96	< 0.005	3.4	< 0.002	22		129									
HP-13	14-Aug-96	1.18	18	0.007	11		14	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
Duplicate HP-13	14-Aug-96	1.18	9.5	0.003	10.3		11.8	< 1.0	< 1.0	< 1.0	< 1.0	< 0.002	< 1.0	< 2.0	< 1.0	< 2.0
HP-14	15-Aug-96	< 0.05	< 0.5	0.004	28		191	< 1.0	1	< 1.0	4	0.005	< 1.0	< 2.0	< 1.0	< 2.0
HP-15	15-Aug-96	< 0.05	1.1	0.003	44		69.8	< 1.0	< 60.0	< 50.0	< 50.0	< 0.06	53	< 2.0	< 50.0	< 2.0
HP-22	5-Oct-96	< 0.2	4.7	0.01			122	< 10	38	< 10	55	0.093	< 10	< 20	< 10	< 20
HP-23	5-Oct-96	< 0.2	7	< 0.002			233	210	180	33	810	1.233	< 1.0	< 30.0	30	< 2.0
HP-24	5-Oct-96	< 0.2	13	0.007			448	490	3100	230	2800	6.42	690	2800	76	< 2.0
HP-25	5-Oct-96	< 0.2	12.4	0.003			183	10	360	50	1010	1.439	< 2.0	1	72	< 2.0
HP-26	5-Oct-96	< 0.2	10.5	0.011			361	1200	3800	260	4800	10.06	< 2.0	3300	125	< 2.0
Duplicate HP-26	5-Oct-96	< 0.2	9.8	0.009			380	1200	3750	270	4900	10.02	< 2.0	3200	115	< 2.0
Manhole	16-Jan-96							< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
SW1	10-Aug-96	< 0.005	1.4	0.003	11		< 0.1	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
SW2	10-Aug-96			0.003	19		1.9	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
SW3	15-Aug-96			0.002			529	< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 2.0	< 1.0	< 2.0
Rinsate Blank	16-Jan-96							< 1.0	1	< 1.0	< 1.0	< 0.001	< 1.0	< 1.0	< 1.0	< 2.0
Rinsate Blank	14-Aug-96							< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 1.0	< 1.0	< 2.0
Rinsate Blank	3-Oct-96							< 1.0	< 1.0	< 1.0	< 1.0	< 0.001	< 1.0	< 1.0	< 1.0	< 2.0

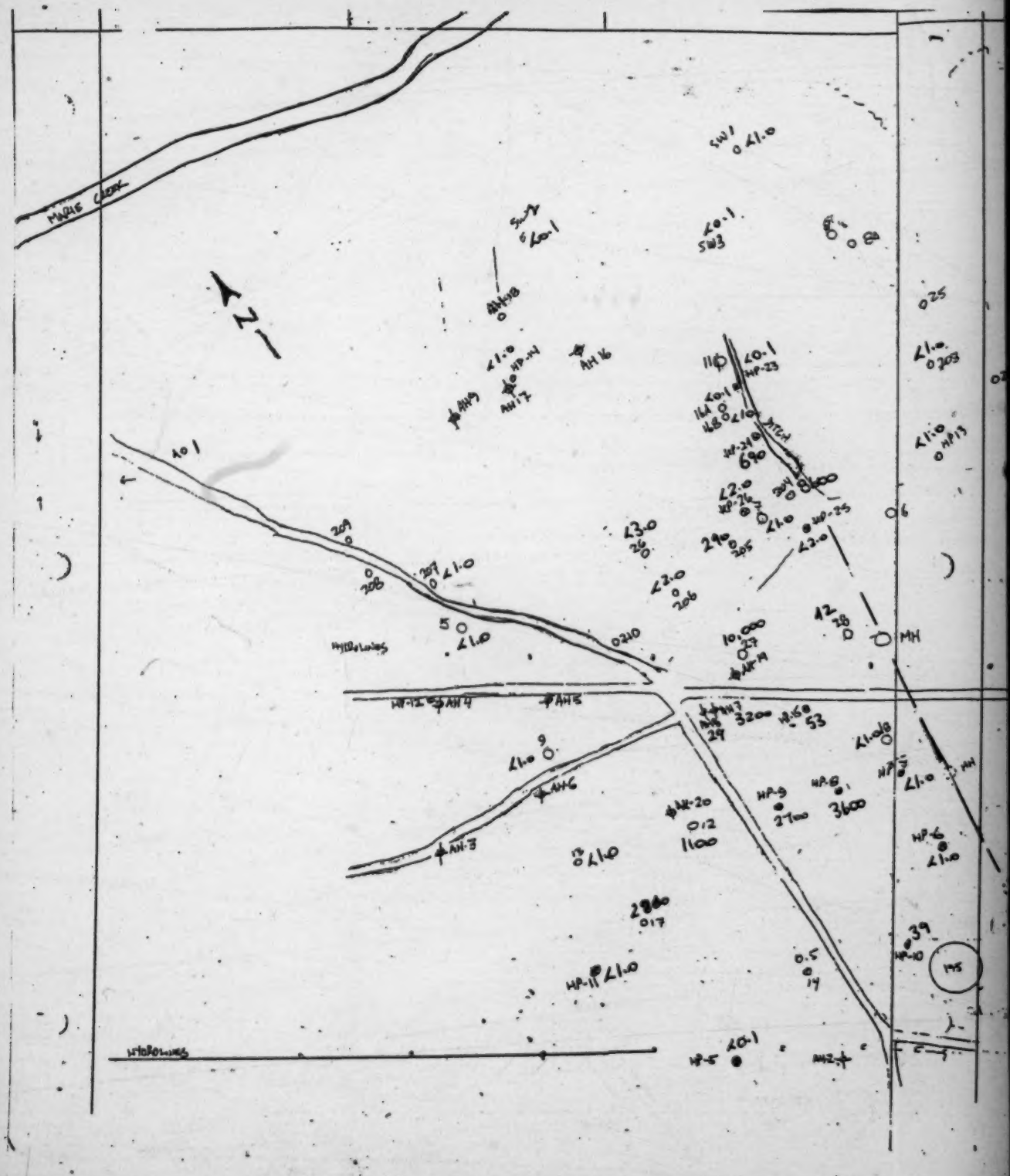
LABORATORY ANALYSIS OF SOIL SAMPLES

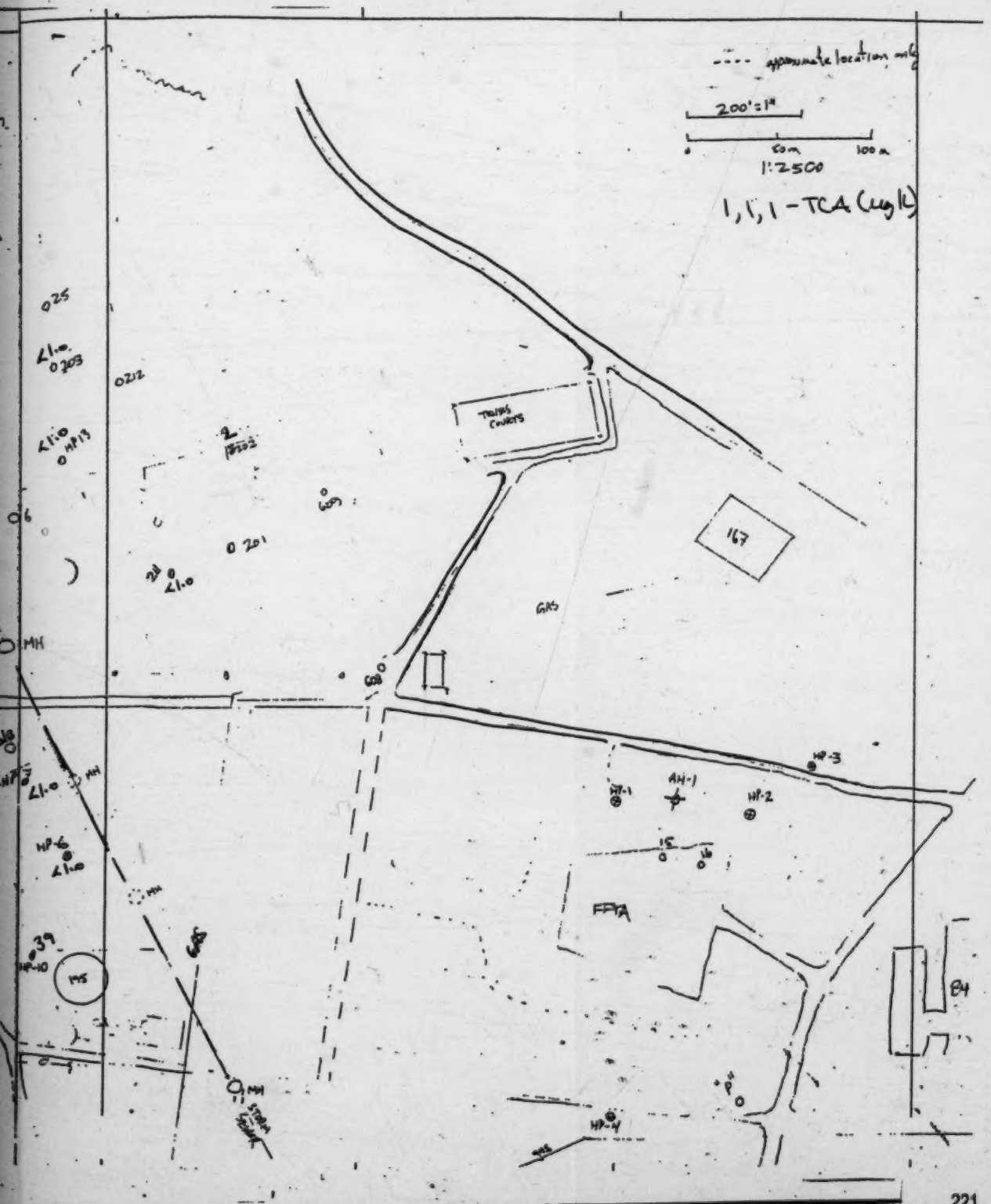
		SOIL SAMPLES SENT TO OUTSIDE LABORATORY FOR ANALYSIS (ug/kg or ppb)										
		DEPTH	ELEVATION	NON-HALOGENTATED AROMATICS				VOLATILE ORGANIC COMPOUNDS				ORGANIC MATTER
DATE	WELL SITE	(m)	(m)	Benzene	Toluene	Ethylbenzene	Xylenes	1,1,1-TCA	1,1-DCA	DCBs	CA	(%)
13-Aug-98	AH-02	2.29	537.284	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 100	NA
13-Aug-98	AH-03	2.13	535.633	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 200	NA
13-Aug-98	AH-04	1.68	535.783	< 10	< 40	< 10	< 10	< 10	< 20	< 10	< 100	NA
13-Aug-98	AH-05	1.83	535.681	< 20	< 20	< 20	< 20	< 20	< 40	< 20	< 200	NA
13-Aug-98	AH-06	2.13	535.921	< 20	< 20	< 20	< 20	< 20	< 40	< 20	< 200	NA
14-Aug-98	AH-07	1.98	536.72	< 300	< 300	< 300	50,000	1,000	< 600	4,000	< 3,000	0.56
14-Aug-98	Duplicate AH-07	1.98	536.72	< 300	< 300	< 300	48,000	980	< 600	4,100	< 3,000	0.56
14-Aug-98	AH-07	2.29	536.41	83	120	23	650	530	120	30	< 100	NA
14-Aug-98	AH-07	3.35	535.35	400	31,000	180	980	< 10	< 120	< 10	< 100	NA
14-Aug-98	AH-08	10.9	527.89	< 20	< 20	< 20	< 20	< 20	< 40	< 20	< 200	NA
15-Aug-98	AH-16	0.3	532.891	< 10	< 10	< 10	< 10	< 10	< 20	< 10	< 100	NA
15-Aug-98	AH-16	0.69	532.501	24	< 20	26	190	< 20	< 40	< 20	< 200	NA
15-Aug-98	AH-17	0.46	533.434	< 10	< 10	< 10	< 10	< 10	< 20	< 10	< 100	NA
5-Oct-98	AH-19	2.36	534.991	340	1900	400	2590	1100	< 20	105	< 100	NA
5-Oct-98	AH-20	2.51	536.137	100	750	440	1220	400	< 20	18	< 100	NA

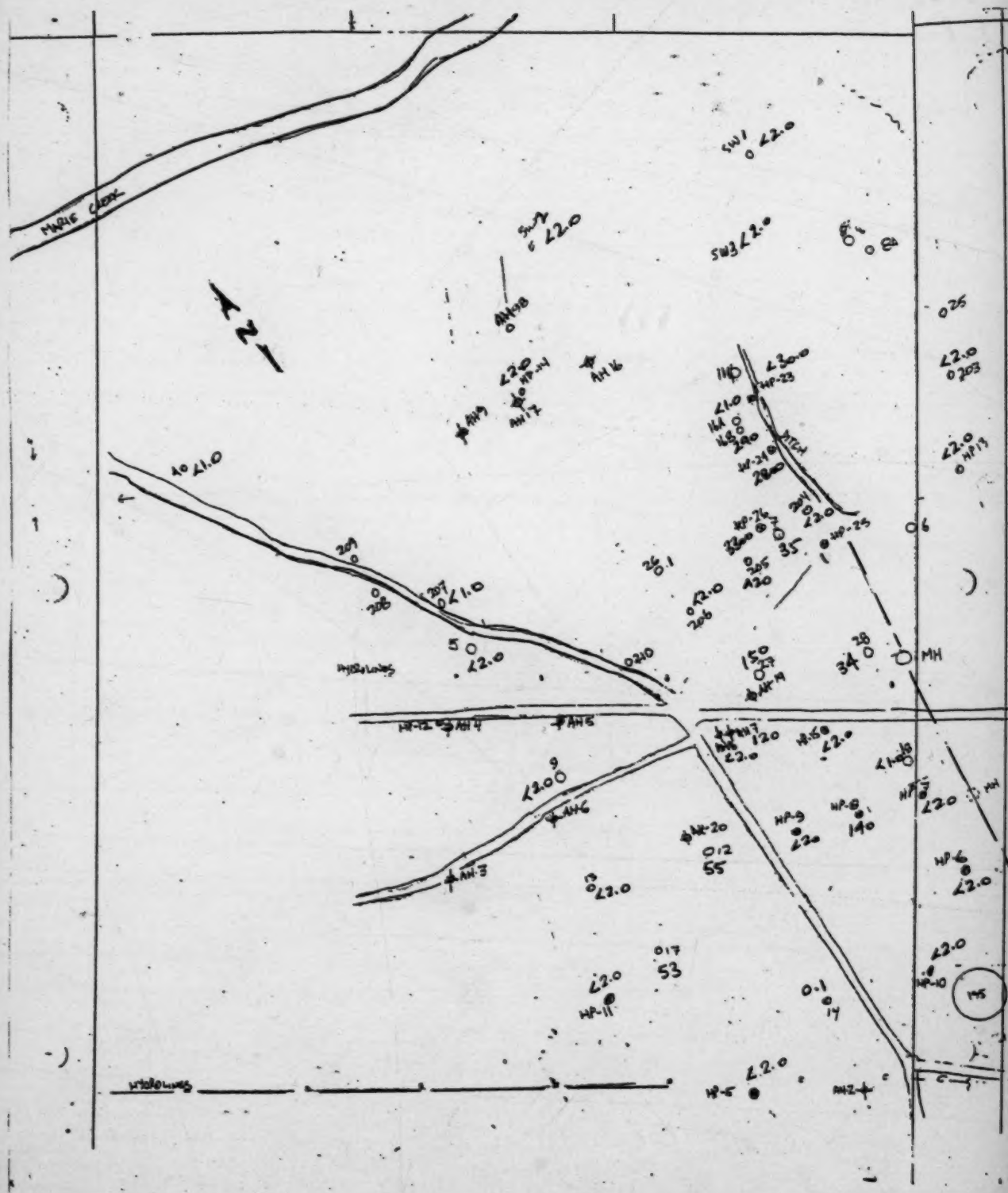
NA not analysed
ND non-detect

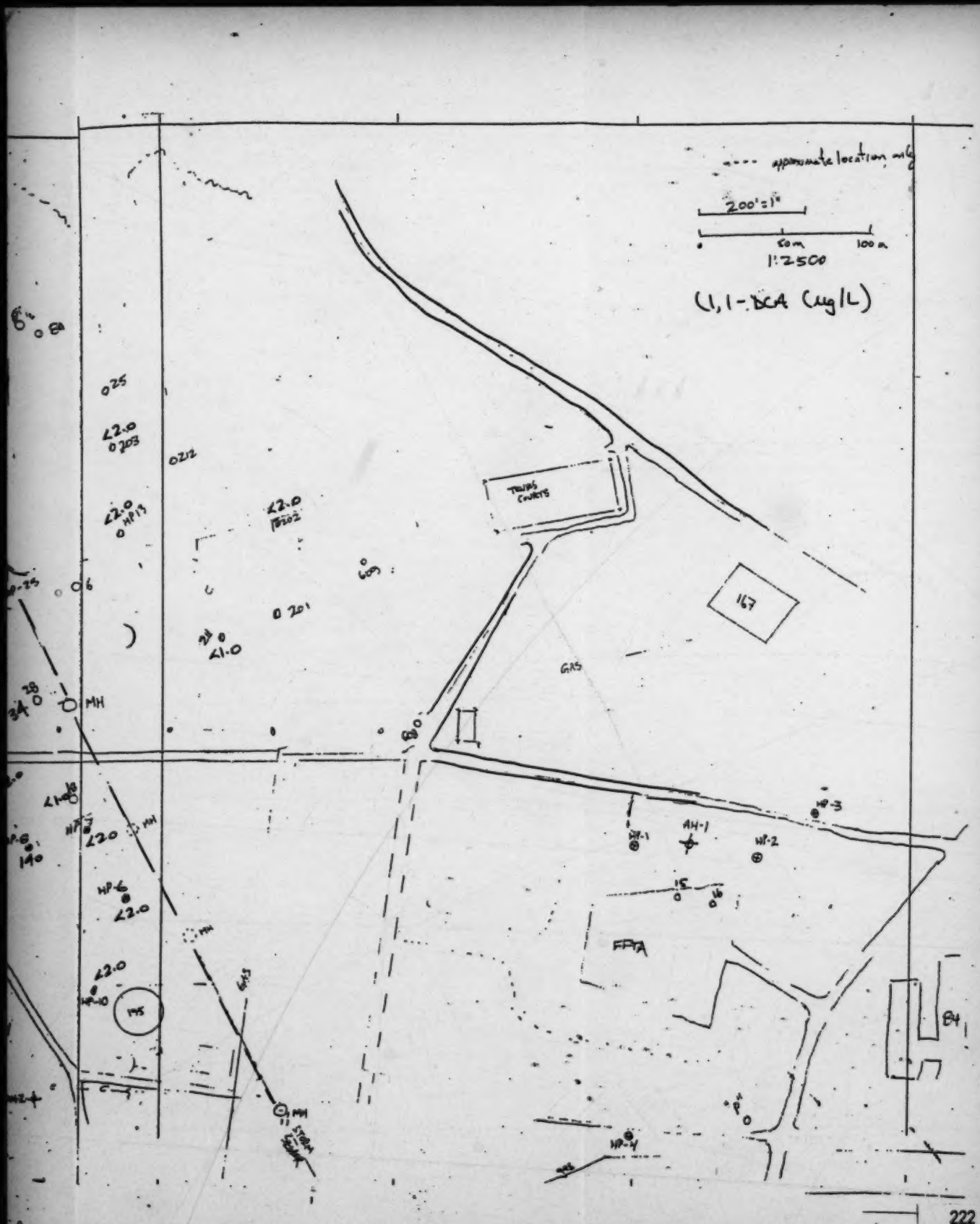

Marble Creek
N
SW1
SW2
SW3
AH-18
AH 16
AH 17
AH 9
HP-14
HP-23
AH-14
HP-24
HP-26
HP-25
AH-19
AH 4
AH 5
AH-12
AH-3
AH 6
AH-20
HP-9
HP-8
HP-3
HP-11
HP-5
AH 2
MH


---- approximate location, mig
200'=1"
50m
100m
1:2500
BTEX (mg/L)
TRAILER COURTS
167
GAS
MH
HP-1
HP-2
HP-3
HP-4
AH-1
FENCE
EH
STORM SEWER


MAPLE CREEK
401
MH
MH
MH


---- approximate location only
200'=1"
0
50m
100m
1:2500
1,1,1-TCA (ug/L)
TRAILER COURTS
167
GAS
MH
HP-1
HP-2
HP-3
HP-4
HP-6
HP-10
AH-1
FENCE
B4
221


MARIE CREEK
SW1
SW2
SW3
AH-10
AH-16
AH-17
AH-14
HP-23
HP-24
HP-25
AH-24
AH-4
AH-5
AH-6
AH-3
HP-11
HP-5
AH-2
HP-10
HP-6
HP-7
HP-8
HP-9
AH-20
MH
HYDROLINES


---- approximate location of
200'=1"
50m
100m
1:2500
(1,1-DCA (ug/L)
TRIPPS COURTS
167
GAS
MH
HP-1
HP-2
HP-3
HP-4
HP-6
HP-10
AH-1
FENCE
STORM SEWER

APPENDIX J:

Most Probable Number Calculations

MPN - Dry Weight Calculations

Sample	Description	Boat mg	Aug 18 2pm Boat +Wet mg	Aug 19 10am Boat +Dry mg - Day 1	Aug 21 11am Boat + Dry mg - Day 3	Dry weight soil only-D3	Wet Weight mg	Weight H2O mg (w Day 3)	$\frac{\text{Weight}_{H2O}}{\text{Weight}_{Soil}}$	Avg
AH-01 (1)	coarse sand	1.008	22.216	18.521	18.512	17.504	21.208	3.704	0.175	
AH-01 (2)	lt gy bn	0.996	23.303	19.427	19.413	18.417	22.307	3.890	0.174	0.170
AH-01 (3)		0.990	21.374	18.084	18.075	17.085	20.384	3.299	0.162	
AH-02 (1)	med-coarse	0.991	17.974	16.348	16.324	15.333	16.983	1.650	0.097	
AH-02 (2)	sand, lt bn	0.997	22.549	20.345	20.315	19.318	21.552	2.234	0.104	0.105
AH-02 (3)		0.989	24.488	21.830	21.804	20.815	23.499	2.684	0.114	
AH-07 (1)	fine silty	0.986	40.48	32.696	32.67	31.684	39.494	7.810	0.198	
AH-07 (2)	sand, lt gy	0.99	30.29	24.385	24.37	23.38	29.300	5.920	0.202	0.198
AH-07 (3)		0.99	22.069	18.011	18.00	17.01	21.079	4.069	0.193	
AH-17 (1)	org+med	1.007	19.266	16.023	15.950	14.943	18.279	3.336	0.183	
AH-17 (2)	sand dkgy-	0.997	16.791	13.147	13.072	12.075	15.794	3.719	0.235	0.210
AH-17 (3)	blk	1.003	23.387	18.713	18.623	17.62	22.384	4.764	0.213	
AH-10 (1)	silty clay	1.000	20.403	17.002	16.921	15.921	19.403	3.482	0.179	
AH-10 (2)	lt gy	1.010	29.762	24.539	24.454	23.444	28.752	5.308	0.185	0.188
AH-10 (3)		1.007	30.643	24.800	24.720	23.713	29.636	5.923	0.200	
AH-14 (1)	silty clay	0.998	35.436	28.462	28.365	27.367	34.438	7.071	0.205	
AH-14 (2)	lt gy	0.997	42.40	33.826	33.74	32.743	41.403	8.660	0.209	0.212
AH-14 (3)		1.01	35.14	27.683	27.60	26.59	34.130	7.540	0.221	
AH-11 (1)	silty clay	0.999	28.35	23.438	23.358	22.359	27.351	4.992	0.183	
AH-11 (2)	lt gy	1.01	27.18	21.528	21.446	20.436	26.170	5.734	0.219	0.213
AH-11 (3)		1.02	26.36	20.445	20.357	19.337	25.340	6.003	0.237	

= slight spillage before massing

Balance: Mettler PC 440
Furnace: 105°C
Into furnace at 1400 hrs Aug 18

ANAEROBIC MPN STUDY

1 source sample (2 or 3 jars combined)
5 tubes per dilution
5 media per sample

Microorganisms	Dilutions	Media Required	+ve Culture
Total Heterotrophs	7	R2A liquid, full strength	Any lab culture
JP-4 Degraders	7	Bushnell-Haas + 50µL filter-sterilised JP-4 (added ***after*** inoculation)	Try Esquimalt sediment dwellers
SRB	4	Modified Butlin's* with nails	AL-1 (see Cathy) or E. coli
NRB	9	Difco Nitrate broth, with inverted Durham vials	P. vulgaris/P aeruginosa (see Cathy)
FeRB	7	B10 medium**	S. putrefaciens

*Combine pyruvate, lactate, acetate, benzoate as substrates, add dithionite just before inoculation
** Prepared by Sara last time

Methodology

- Does 45 mL of 0.1% (w/v) Na pyrophosphate per dilution bottle (9) (check pH)
- Add 10 mL of medium to each TT as required
- Autoclave and cool, leave in O_2 hood
- Purge source serum vials with filter sterilised N_2 gas for 2 hours to remove 14C toluene
- Shimmy in reciprocating shaker for ~ 30 min to free microorganisms from soil
- In O_2 hood: add 30 mL to 10^0 dilution bottle
  - Subsample 10 mL into sequential serial dilution bottles up to 10^{-9}
  - Aseptically pipette 1 mL of appropriate dilution into test tubes with media and caputs

Equipment

10 x dilution bottles
R2A medium [(7 x 5) + 4] x 10 mL = 390 mL — make 500 mL
B-H [(7 x 5) +4] x 10 = 390 mL — make 500 mL
Butlin's [(4 x 5) + 4] x 10 mL = 240 mL — make 500 mL
Difco [(9 x 5) + 4] x 10 mL = 490 mL — make 1L
B10 [(7 x 5) +4] x 10mL = 390 mL — make 500 mL
Sterilised JP-4 = 24 x 50 µL = 1.2 mL — make 4 mL
Test tubes 175
Phosphate buffer = 90 mL x 9 dilutions = 360 mL
Miscellaneous pipettes 10 mL, 25 mL
Durham vials 1 x 5x 9 = 45 tubes
Nails 2 x 5 x 7 = 70 nails

Media Used for Each Group of Microorganisms

Group being Enumerated	Medium	Positive Culture Used
Total Heterotrophs	R2A liquid, full strength	A lab culture
JP-4 Degraders	Bushnell-Haas + 50µL filter-sterilised JP-4	An 8°C JP-8 maintenance culture
Sulfate Reducers	Modified Butlin's broth, with nails	AL-1
Nitrate Reducers	Difco Nitrate broth, with inverted Durham vials	*Pseudomonas aeruginosa, Proteras vulgaris.*
Iron Reducers	B10 medium**	*Shewanella putrefaciens*

Recipes

R2A Liquid (Total Heterotrophs)

Source: Atlas, Ronald. 1993. Handbook of Microbiological Media, CRC press, Boca Raton, Fl. Lawrence C parks, editor.

Per litre

0.5g yeast extract
0.5g casamino acid
0.5g glucose
0.5g soluble starch
0.5g K_2HPO_4
0.3g Sodium Pyruvate
0.25g tryptone
0.25g peptone
0.024g $MgSO_4$, anhydrous

Bushnell-Haas (JP-4 degraders)

Source: Difco Manual, 1984. Dehydrated Culture Media and Reagents for Microbiology. 10th ed., Difco Laboratories, Detroit, MI.

Per litre

0.2g $MgSO_4$
0.02g CaCl
1g Monopotassium Phosphate
1g Dipotassium Phosphate
1g Ammonium Nitrate
0.05g FeCl

Modified Butlin's (Sulfate Reducers)

Source: after Butlin, et al., 1949. Journal of General Microbiology, 3:46-49

Per litre

0.5g	K_2HPO_4	1g	NaCl
1g	NH_4Cl	0.5g	sodium benzoate
2g	Na_2SO_4	2.1g	sodium pyruvate
1g	$MgSO_4.7H_2O$	1g	yeast extract
0.07g	$CaCl_2.2H_2O$	0.004g	$FeSO_4.7H_2O$
2.5mL	60% sodium lactate	10 mL	resazurin
2g	sodium acetate		

Difco Nitrate Broth

Source: Difco Manual, 1984. Dehydrated Culture Media and Reagents for Microbiology. 10th ed., Difco Laboratories, Detroit, MI.

Per litre

3g	Bacto beef extract
5g	Bacto Peptone
1g	Potassium nitrate

B10 Media

Source: C. Panter, M.Sc. thesis, C.O. Obuekwe, Ph.D. thesis.

Per litre

0.8g	K_2HPO_4	10mL	$CaSO_4$ (saturated)
0.2g	KH_2PO_4	5g	yeast extract
0.2g	$MgSO_4.7H_2O$	5g	Bacto peptone
0.2g	NaCl	4.7g	$FePO_4$
1mL	0.1% $MnSO_4$	2.5g	agar
1mL	0.1% $NaMO_4$		

MPN Week Four (@6deg)

Site	Sample	Char #	dilution first value	min (95%C	MPN from table	max (95%C	Dilution correction MPN/g wet soil added	Mass Soil used Correction MPN/g wet soil	wet/dry soil ratio	Soil Moisture Correction MPN/g dry	min (95%CI)	max (95%CI)
Landfill Background	NRB >nitrite	5-5-3	0.0001	23.0	92.0	253.0	920000	9.15E+05	1.12	1.0E+06	2.6E+05	2.6E+06
AH-02	NRB >N_2 gas	5-2-3	0.001	3.0	12.0	24.0	12000	1.19E+04	1.12	1.3E+04	3.3E+03	2.7E+04
	FeRB	5-2-1	0.01	2.2	7.0	16.8	700	6.97E+02	1.12	7.8E+02	2.5E+02	1.9E+03
	SRB	0-0-0		0.0	0.0	0.0	0	0.00E+00	1.12	0.0E+00	0.0E+00	0.0E+00
week 5	JP-4	4-0-0	0.1	0.4	1.3	3.4	13	1.29E+01	1.12	1.4E+01	4.5E+00	3.8E+01
	Total Het	5-3-0	0.00001	2.3	7.9	22.0	790000	7.86E+05	1.12	8.8E+05	2.6E+05	2.5E+06
Landfill Plume	NRB >nitrite	5-3-0	0.001	2.3	7.9	22.0	7900	7.90E+03	1.25	9.9E+03	2.9E+03	2.8E+04
AH-07	NRB >N_2 gas	5-4-1	0.01	6.0	17.0	39.0	1700	1.70E+03	1.25	2.1E+03	7.5E+02	4.9E+03
	FeRB	5-4-1	0.1	6.0	17.0	39.0	170	1.70E+02	1.25	2.1E+02	7.5E+01	4.9E+02
	SRB	1-0-0	0.001	0.02	0.20	0.99	200	2.00E+02	1.25	2.5E+02	2.5E+01	1.2E+03
week 5	JP-4	8-0-0	0.01	0.7	2.3	6.6	230	2.30E+02	1.25	2.9E+02	8.8E+01	8.3E+02
	Total Het	5-3-1	0.001	3.0	11.0	24.0	11000	1.10E+04	1.25	1.4E+04	3.8E+03	3.0E+04
Landfill downstrea	NRB >nitrite	5-3-0	0.0001	2.3	7.9	22.0	79000	7.83E+04	1.27	9.9E+04	2.9E+04	2.8E+05
AH-17	NRB >N_2 gas	5-4-1	0.001	6.0	17.0	39.0	17000	1.68E+04	1.27	2.1E+04	7.6E+03	4.9E+04
	FeRB	5-3-0	0.01	2.3	7.9	22.0	790	7.83E+02	1.27	9.9E+02	2.9E+02	2.8E+03
	SRB	5-0-0	0.1	0.7	2.3	6.6	23	2.28E+01	1.27	2.9E+01	8.8E+00	8.3E+01
week 5	JP-4	5-0-0	0.01	0.7	2.3	6.6	230	2.28E+02	1.27	2.9E+02	8.8E+01	8.3E+02
	Total Het	5-3-0	0.0001	2.3	7.9	22.0	79000	7.83E+04	1.27	9.9E+04	2.9E+04	2.8E+05

MPN SUMMARY

Summary: After week 4 @6°C MPN/g dry soil			
NRB >nitrite	background 1.0E + 09	plume 9.9E+03	downstream 9.9E+04
NRB >H2	background 1.3E+04	plume 2.1E+03	downstream 2.1E+04
FeRB	background 7.8E+02	plume 2.1E+02	downstream 9.9E+02
SRB	background 0.0E+00	plume 2.5E+02	downstream 2.9E+01

Summary: After week 5 @6°C MPN/g dry soil			
JP-4	background 1.4E+01	plume 2.9E+02	downstream 2.9E+02
Total Het.	background 8.8E+05	plume 1.4E+04	downstream 9.9E+04

MPN Week Six (@22deg)

Site	Sample	Week SIX (2 weeks @22deg) Char #	dilution	MPN			Dilution correction	Mass Soil used	wet/dry soil ratio	MPN Soil Moisture Corrected	95% Confindence Interval MPN	MPN
			first value	in (95%C.I	max (95%CI	expected	MPN/g wet soil added	rrection MPN/g wet soil		MPN/g dry soil	min #/g dry wt	max #/g dry wt
Background	NRB >nitrite	5-3-0	0.00001	2.3	22.0	7.9	790000	7.86E+05	1.12	8.8E+05	2.6E+06	2.5E+06
AH-02	NRB >N_2 gas	5-2-3	0.001	3.0	24.0	12.0	12000	1.19E+04	1.12	1.3E+04	3.3E+03	2.7E+04
	FeRB	5-2-1	0.01	2.2	16.8	7.0	700	6.97E+02	1.12	7.8E+02	2.5E+02	1.9E+03
	SRB	0-0-0				0.0	0	0.00E+00	1.12	0.0E+00		
week 6	JP-4	5-0-0	0.1	0.7	6.6	2.3	23	2.29E+01	1.12	2.6E+01	7.8E+00	7.4E+01
	Total Het	5-4-0	0.00001	3.0	35.0	13.0	1300000	1.29E+06	1.12	1.4E+06	3.3E+05	3.9E+06
Plume	NRB >nitrite	5-3-1	0.001	3.0	24.0	11.0	11000	1.10E+04	1.25	1.4E+04	3.8E+03	3.0E+04
AH-07	NRB >N_2 gas	5-4-1	0.01	6.0	39.0	17.0	1700	1.70E+03	1.25	2.1E+03	7.5E+02	4.9E+03
	FeRB	5-0-0	0.001	0.70	6.60	2.30	2300	2.30E+03	1.25	2.9E+03	8.8E+02	8.3E+03
	SRB	3-1-2	0.001	0.6	3.4	1.7	1700	1.70E+03	1.25	2.1E+03	7.5E+02	4.3E+03
week 6	JP-4	5-3-2	0.01	5.0	35.0	14.0	1400	1.40E+03	1.25	1.8E+03	6.3E+02	4.4E+03
	Total Het	5-3-3	0.0001	7.0	39.0	17.0	170000	1.70E+05	1.25	2.1E+05	8.8E+04	4.9E+05
downstream	NRB >nitrite	5-3-0	0.0001	2.3	22.0	7.9	79000	7.83E+04	1.27	9.9E+04	2.9E+04	2.8E+05
AH-17	NRB >N_2 gas	5-4-1	0.001	6.0	39.0	17.0	17000	1.68E+04	1.27	2.1E+04	7.6E+03	4.9E+04
	FeRB	5-4-0	0.01	3.0	35.0	13.0	1300	1.29E+03	1.27	1.6E+03	3.8E+02	4.4E+03
	SRB	5-0-0	0.1	0.7	6.6	2.3	23	2.28E+01	1.27	2.9E+01	8.8E+00	8.3E+01
week 6	JP-4	5-2-0	0.01	1.5	14.9	4.9	490	4.86E+02	1.27	6.2E+02	1.9E+02	1.9E+03
	Total Het	5-0-0	0.00001	0.7	6.6	2.3	230000	2.28E+05	1.27	2.9E+05	8.8E+04	8.3E+05

MPN SUMMARY

Summary: After week 6 @22°C MPN/g dry soil			
NRB >nitrite	background 8.8E+05	plume 13750	downstream 9.9E+04
NRB >N2	background 1.3E+04	plume 2.1E+03	downstream 2.1E+04
FeRB	background 7.8E+02	plume 2.9E+03	downstream 1.2E+03
SRB	background 0.0E+00	plume 2.1E+03	downstream 2.9E+01

Summary: After week 6 @22°C MPN/g dry soil			
JP-4 degraders	background 2.6E+01	plume 1.8E+03	downstream 6.2E+02
Total Heterotrophs	background 1.4E+06	plume 2.1E+05	downstream 2.9E+05

MPN SAMPLE CALCULATION

AH-02 (Background) at 6°C, week 4

Score from positive and negative test tubes: 5-5-3

First positive score found at dilution: 0.0001

From MPN Table (Alef and Nannipieri, 1995)

MIN. 95% CONFIDENCE INTERVAL	MPN	MAX. 95% CONFIDENCE INTERVAL
23	92	253

Dilution Correction:

$$\frac{92 \text{ MPN}}{0.0001} = 920{,}000 \text{ MPN}$$

Correction for Mass of Soil Used (MPN / g wet soil):

$$\frac{920{,}000 \text{ MPN}}{1.005\text{g wet soil}} = 9.15 \times 10^5 \text{ MPN / g wet soil}$$

Correction of Soil Moisture (MPN / g dry soil)

$$\frac{\text{wet}}{\text{dry}} \text{ soil ratio} = 1.12$$

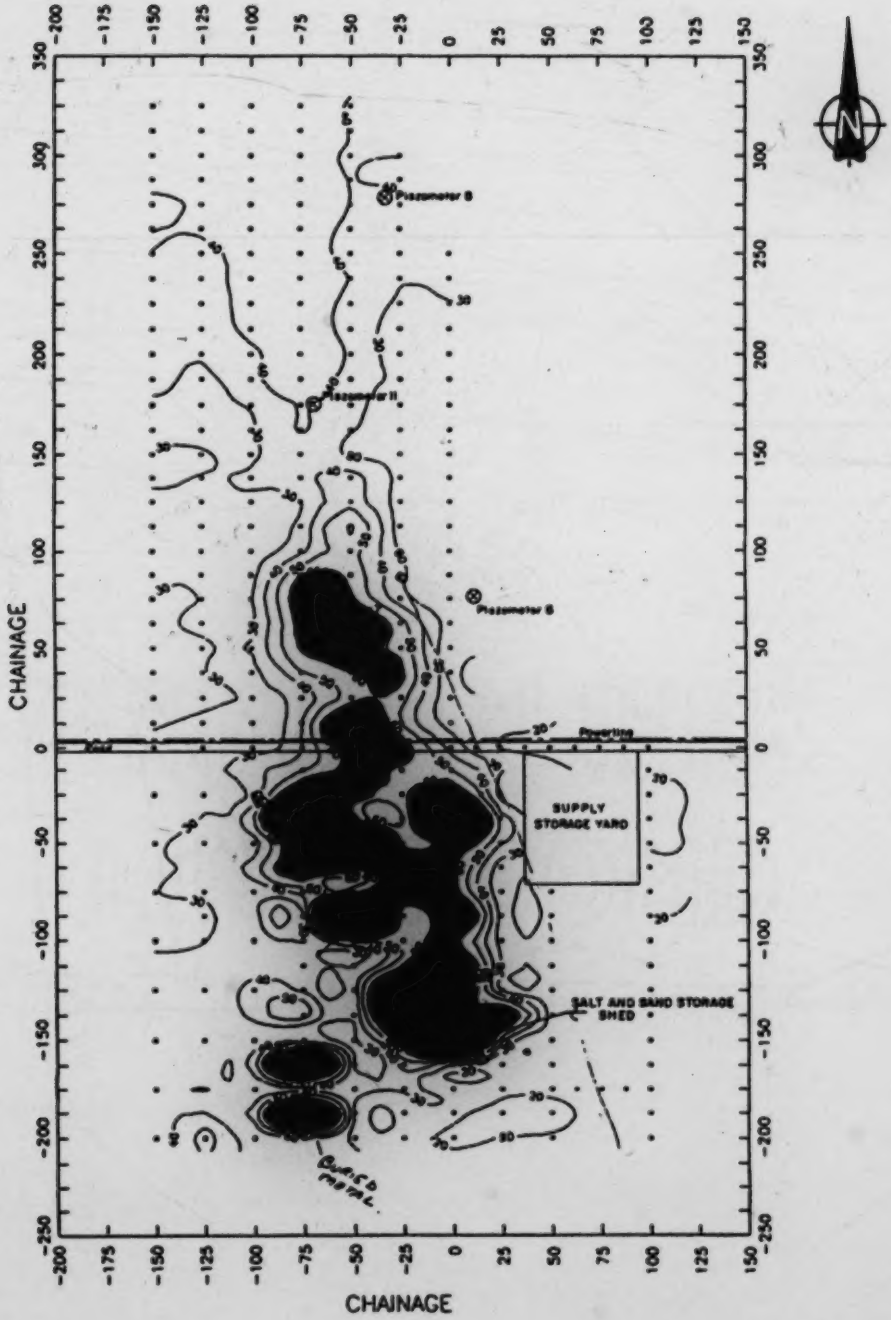
$$9.15 \times 10^5 \times 1.12 = 1.0 \times 10^6 \text{ MPN / g dry soil}$$

Repeat above steps for minimum and maximum confidence intervals. Therefore corrected values are:

MIN. 95% CONFIDENCE INTERVAL	MPN	MAX. 95% CONFIDENCE INTERVAL
2.6×10^5	1.0×10^6	2.8×10^6

APPENDIX K:

Electromagnetic Survey, RRMC 1991

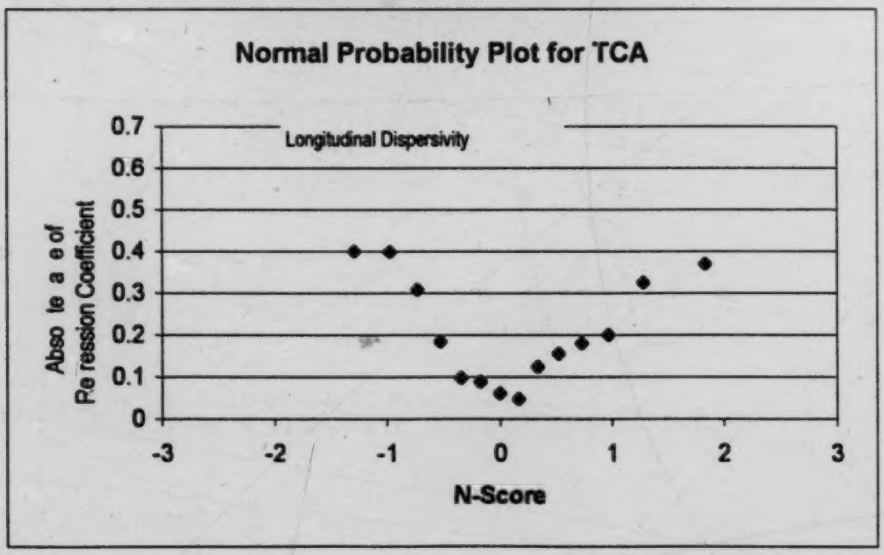

CHAINAGE
CHAINAGE
Piezometer 8
Piezometer 11
Piezometer 6
Pipeline
SUPPLY STORAGE YARD
SALT AND SAND STORAGE SHED
N

APPENDIX L:

BIOCHLOR Analysis

PROBABILITY PLOT FOR TCA

TCA PROBABILITY PLOT					
Effect	Coefficient	ABS	(2i-1)/2n	n-score	ABS
a	-0.64925	0.64925	0.033333	-1.83391	0.64925
d	-0.3995	0.3995	0.1	-1.28155	0.3995
b	-0.39825	0.39825	0.166667	-0.96742	0.39825
c	-0.30725	0.30725	0.233333	-0.72791	0.30725
abd	-0.184	0.184	0.3	-0.5244	0.184
acd	-0.097	0.097	0.366667	-0.34069	0.097
abc	-0.08875	0.08875	0.433333	-0.16789	0.08875
bcd	-0.061	0.061	0.5	0	0.061
abcd	0.0475	0.0475	0.566667	0.167894	0.0475
cd	0.1235	0.1235	0.633333	0.340694	0.1235
bc	0.15475	0.15475	0.7	0.524401	0.15475
ac	0.18025	0.18025	0.766667	0.727913	0.18025
bd	0.2	0.2	0.833333	0.96742	0.2
ab	0.32475	0.32475	0.9	1.281551	0.32475
ad	0.3695	0.3695	0.966667	1.833914	0.3695

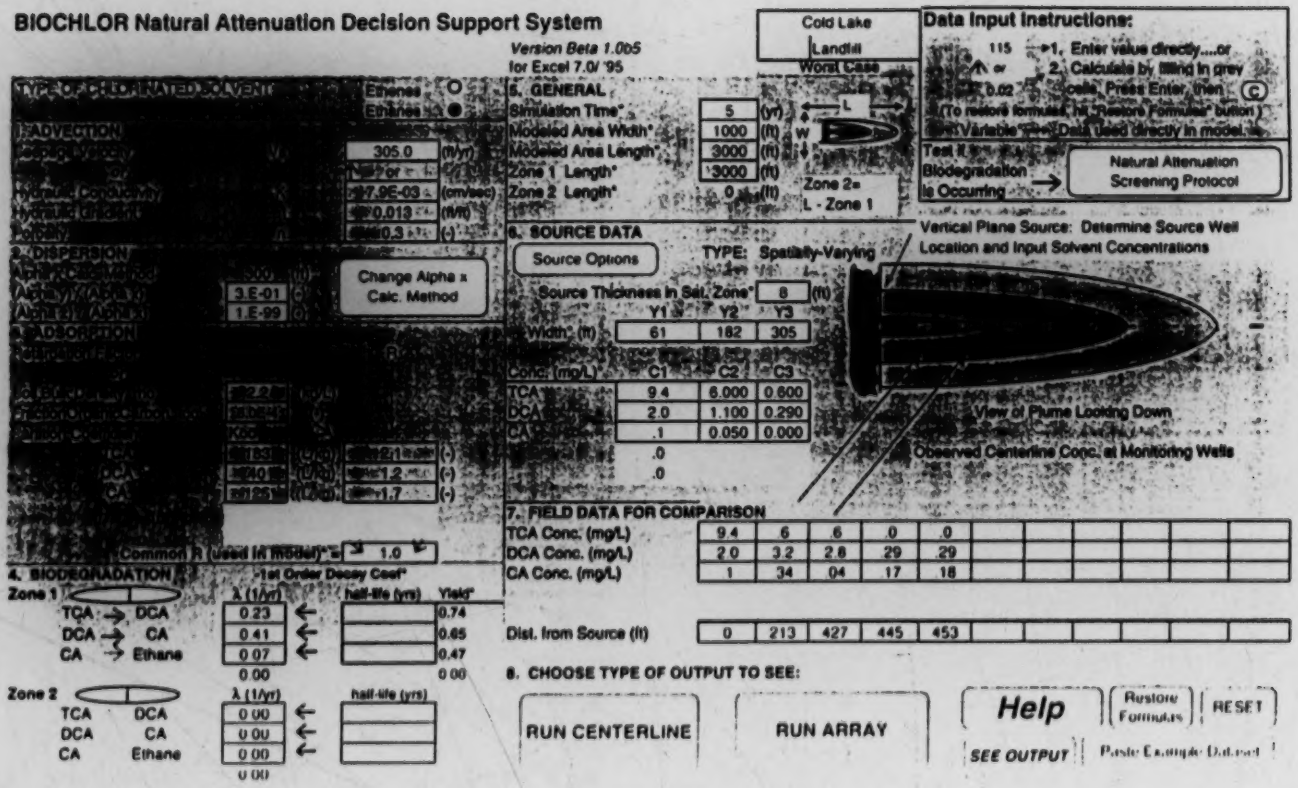


FACTORIAL DESIGN FOR BIOCHLOR MODELLING

Factor			Range -	Range +
A	longitudinal dispersio	(ft)	3.28	300
B	transverse dispersion	(ft)	0.03	0.3
C	vertical dispersion	(ft)	1 X e-99	0.1
D	biodegradation rate	(1/yr)	0.23	2

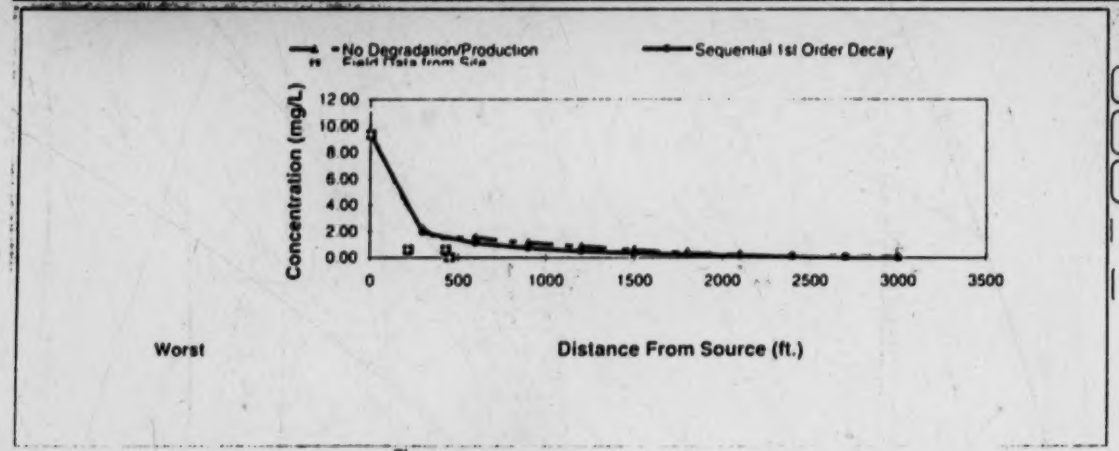
NOTES:
3.28 chosen based on Dr. Mendoza's recommendation (1m)
300 (10% of modelled plume length, generally used in modelling)
As recommended by Dr. Mendoza
Outcome is predicted biodegradation concentration at 300ft minus predicted biodegradation concentration at 1200ft

TRIAL	a	b	c	d	ab	ac	ad	bc	bd	cd	abc (e)	bcd (f)	acd	abd	abcd	Outcome TCA
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1	2.188
2	1	-1	-1	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	0.247
3	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1	1	-1	0.729
4	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	1	1	-1	1	0.078
5	-1	-1	1	-1	1	-1	1	-1	1	-1	1	1	1	-1	-1	1.128
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1	0.014
7	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	1	0.373
8	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1	0.004
9	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1	0.706
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	0.161
11	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	0.232
12	1	1	-1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	0.051
13	-1	-1	1	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1	0.304
14	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1	0.008
15	-1	1	1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	0.1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.003
															Stdev	0.576


BIOCHLOR Natural Attenuation Decision Support System
Version Beta 1.0b5
for Excel 7.0/ '95
Cold Lake
Landfill
Worst Case
Data Input Instructions:
1. Enter value directly....or
2. Calculate by filling in grey cells. Press Enter, then
(To restore formulas hit "Restore Formulas" button)
Variable "Red" Data used directly in model.
Test if Biodegradation is Occurring
Natural Attenuation Screening Protocol
TYPE OF CHLORINATED SOLVENT
Ethene
Ethane
1. ADVECTION
305.0
7.9E-03
0.013
0.3
2. DISPERSION
3.E-01
1.E-99
Change Alpha x Calc. Method
3. ADSORPTION
1.2
1.7
Common R (used in model)* = 1.0
4. BIODEGRADATION
Zone 1
-1st Order Decay Coef*
λ (1/yr)
half-life (yrs)
Yield*
TCA → DCA 0.23 0.74
DCA → CA 0.41 0.65
CA → Ethane 0.07 0.47
0.00 0.00
Zone 2
TCA DCA 0.00
DCA CA 0.00
CA Ethane 0.00
0.00
5. GENERAL
Simulation Time* 5 (yr)
Modeled Area Width* 1000 (ft)
Modeled Area Length* 3000 (ft)
Zone 1 Length* 3000 (ft)
Zone 2 Length* 0 (ft)
Zone 2= L - Zone 1
6. SOURCE DATA
Source Options
TYPE: Spatially-Varying
Source Thickness in Sat. Zone* 8 (ft)
Y1 Y2 Y3
Width* (ft) 61 182 305
Conc. (mg/L)* C1 C2 C3
TCA 94 6.000 0.600
DCA 2.0 1.100 0.290
CA .1 0.050 0.000
.0
.0
Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations
View of Plume Looking Down
Observed Centerline Conc. at Monitoring Wells
7. FIELD DATA FOR COMPARISON
TCA Conc. (mg/L) 94 6 .6 .0 .0
DCA Conc. (mg/L) 2.0 3.2 2.8 29 29
CA Conc. (mg/L) 1 34 04 17 18
Dist. from Source (ft) 0 213 427 445 453
8. CHOOSE TYPE OF OUTPUT TO SEE:
RUN CENTERLINE
RUN ARRAY
Help
Restore Formulas
RESET
SEE OUTPUT
Paste Example Dataset

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

TCA	Distance from Source (ft)										
	0	600	1200	1800	2400	3000	3600	4200	4800	5400	6000
No Degradation	9.400	2.239	1.530	1.154	0.881	0.657	0.469	0.316	0.200	0.116	0.064
Biodegradation	9.400	1.885	1.101	0.723	0.491	0.331	0.218	0.138	0.083	0.047	0.025
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	9.400	0.600	0.600	0.000	0.000						



See TCA

See DCA

See CA

Log ⟺ Linear

Time:

5 Years

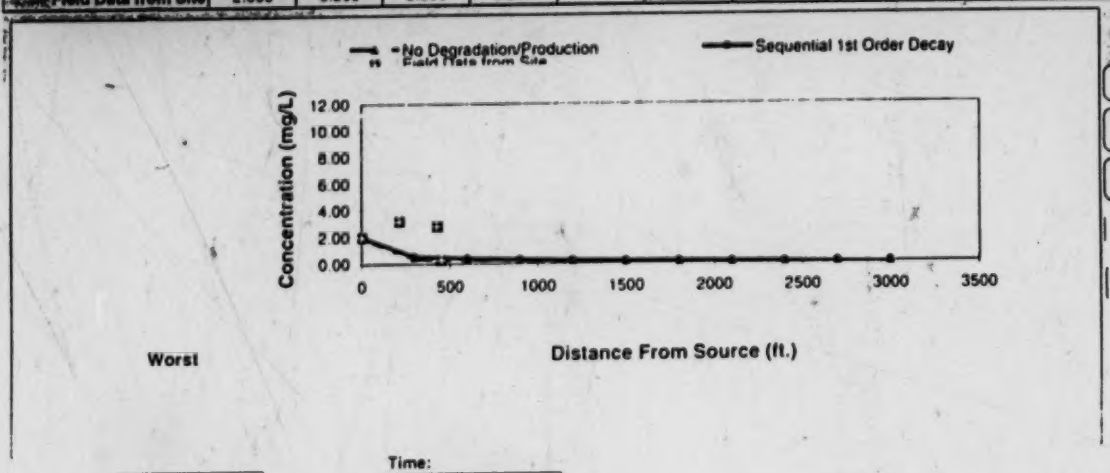
Return to Input

To All

To Array

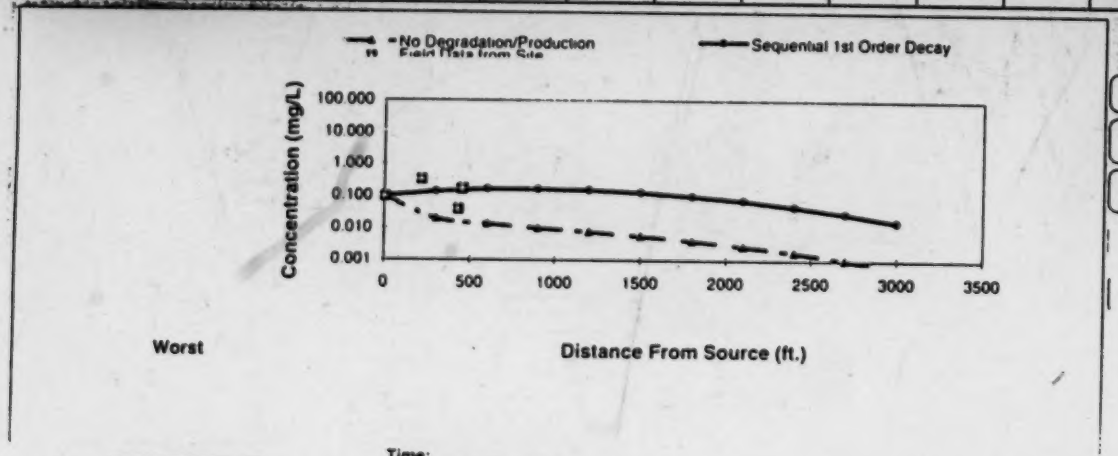
DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

DCA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	2.000	0.471	0.323	0.244	0.186	0.139	0.099	0.067	0.042	0.025	0.014
Biodegradation	2.000	0.547	0.395	0.301	0.227	0.166	0.116	0.076	0.047	0.027	0.015
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	2.000	3.200	2.800	0.290	0.290						



DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

CA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	0.100	0.020	0.014	0.010	0.008	0.006	0.004	0.003	0.002	0.001	0.001
Biodegradation	0.100	0.134	0.161	0.165	0.153	0.129	0.101	0.072	0.048	0.029	0.016
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	0.100	0.340	0.040	0.170	0.160						



See TCA

See DCA

See CA

Worst

Log ⟺ Linear

Time:

5 Years

Return to Input

To All

To Array

BIOCHLOR Natural Attenuation Decision Support System

Version Beta 1.0b5
for Excel 7.0/ '95

Cold Lake
Landfill
Best Case

Data Input Instructions:

115 1: Enter value directly ... or
or 2: Calculate by filling in grey
0.01 cells. Press Enter, then C
(To restore formulas, hit "Restore Formulas" button)
Red Variable = Data used directly in model.

Test if Biodegradation is Occurring → Natural Attenuation Screening Protocol

TYPE OF CHLORINATED SOLVENT: Ethenes / Ethanes

1. ADVECTION
91.0 (ft/yr) or
7.9E-03 (cm/sec)
0.013 (ft/ft)
0.3 (-)

2. DISPERSION
Change Alpha x Calc. Method
3.E-02
1.E-99

ADSORPTION
TCA 2.1 (-)
DCA 1.2 (-)
CA 1.7 (-)

Common R (used in model)* = 1.0

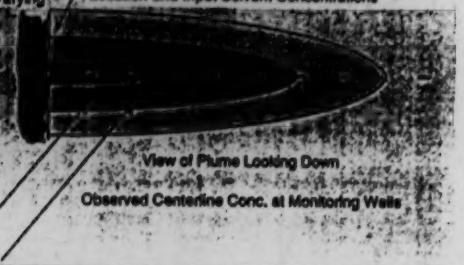
3. GENERAL
Simulation Time* 5 (yr)
Modeled Area Width* 1000 (ft)
Modeled Area Length* 3000 (ft)
Zone 1 Length* 3000 (ft)
Zone 2 Length* 0 (ft)
Zone 2 = L - Zone 1

5. SOURCE DATA
Source Options
TYPE: Spatially-Varying
Source Thickness in Sat. Zone* 8 (ft)

	Y1	Y2	Y3
Width* (ft)	61	182	305

Conc. (mg/L)*	C1	C2	C3
TCA	94	6.000	0.600
DCA	20	1.100	0.290
CA	1	0.050	0.000
	0		
	0		

Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations



4. BIODEGRADATION -1st Order Decay Coef*

Zone 1	λ (1/yr)	half-life (yrs)	Yield*
TCA → DCA	2.00		0.74
DCA → CA	1.98		0.65
CA → Ethane	0.31		0.47
	0.00		0.00

Zone 2	λ (1/yr)	half-life (yrs)
TCA DCA	0.00	
DCA CA	0.00	
CA Ethane	0.00	
	0.00	

7. FIELD DATA FOR COMPARISON

TCA Conc. (mg/L)	94	6	6	0	0							
DCA Conc. (mg/L)	20	32	28	29	29							
CA Conc. (mg/L)	1	34	04	17	18							
Dist. from Source (ft)	0	213	427	445	453							

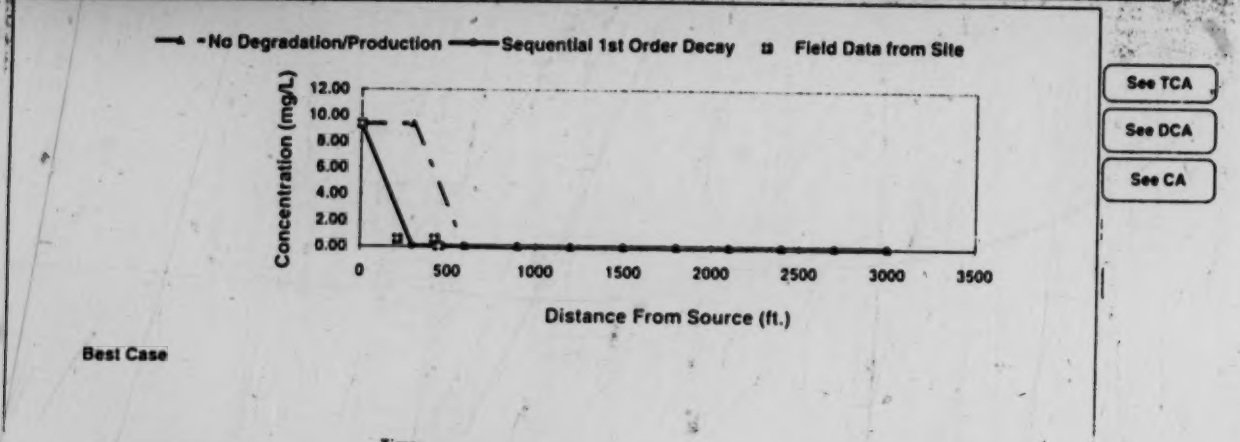
8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE | RUN ARRAY | Help | Restore Formulas | RESET

SEE OUTPUT | Paste Example Dataset

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

TCA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	9.400	9.378	0.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	9.400	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	9.400	0.600	0.600	0.000	0.000						



See TCA

See DCA

See CA

Best Case

Log ⟺ Linear

Time:

5 Years

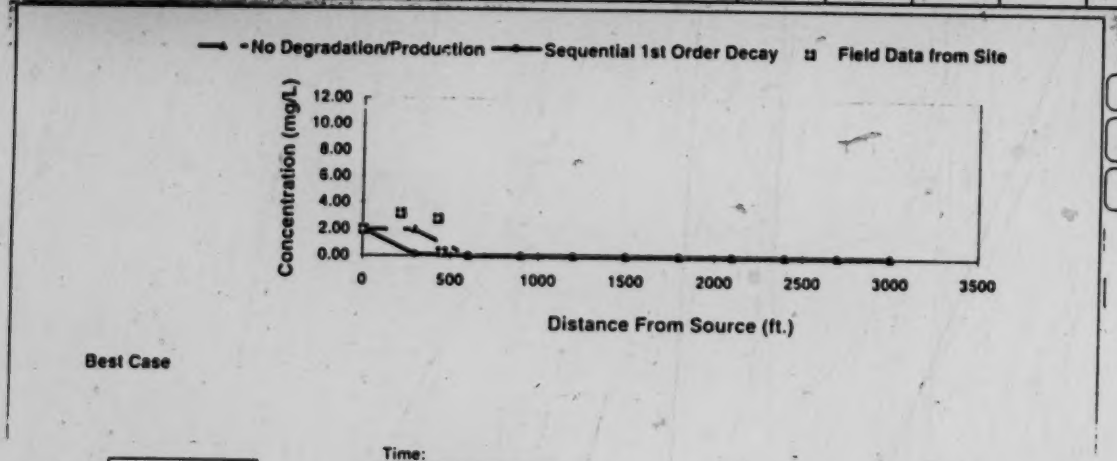
Return to Input

To All

To Array

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

DCA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	2.000	1.995	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	2.000	0.091	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	2.000	3.200	2.800	0.290	0.290						



See TCA

See DCA

See CA

Best Case

Log ⟺ Linear

Time: 5 Years

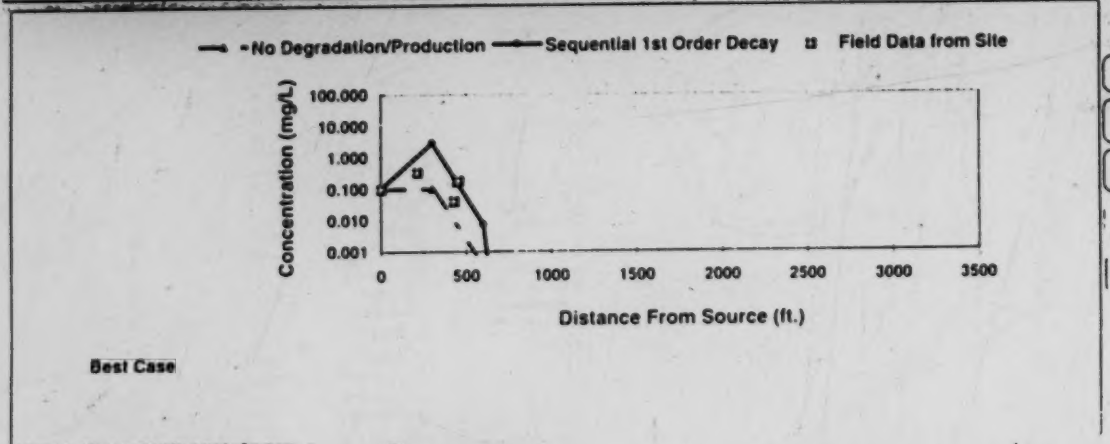
Return to Input

To All

To Array

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

CA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	0.100	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	0.100	2.833	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Monitoring Well Locations (ft)										
	0	213	427	446	453						
Field Data from Site	0.100	0.340	0.040	0.170	0.180						



See TCA

See DCA

See CA

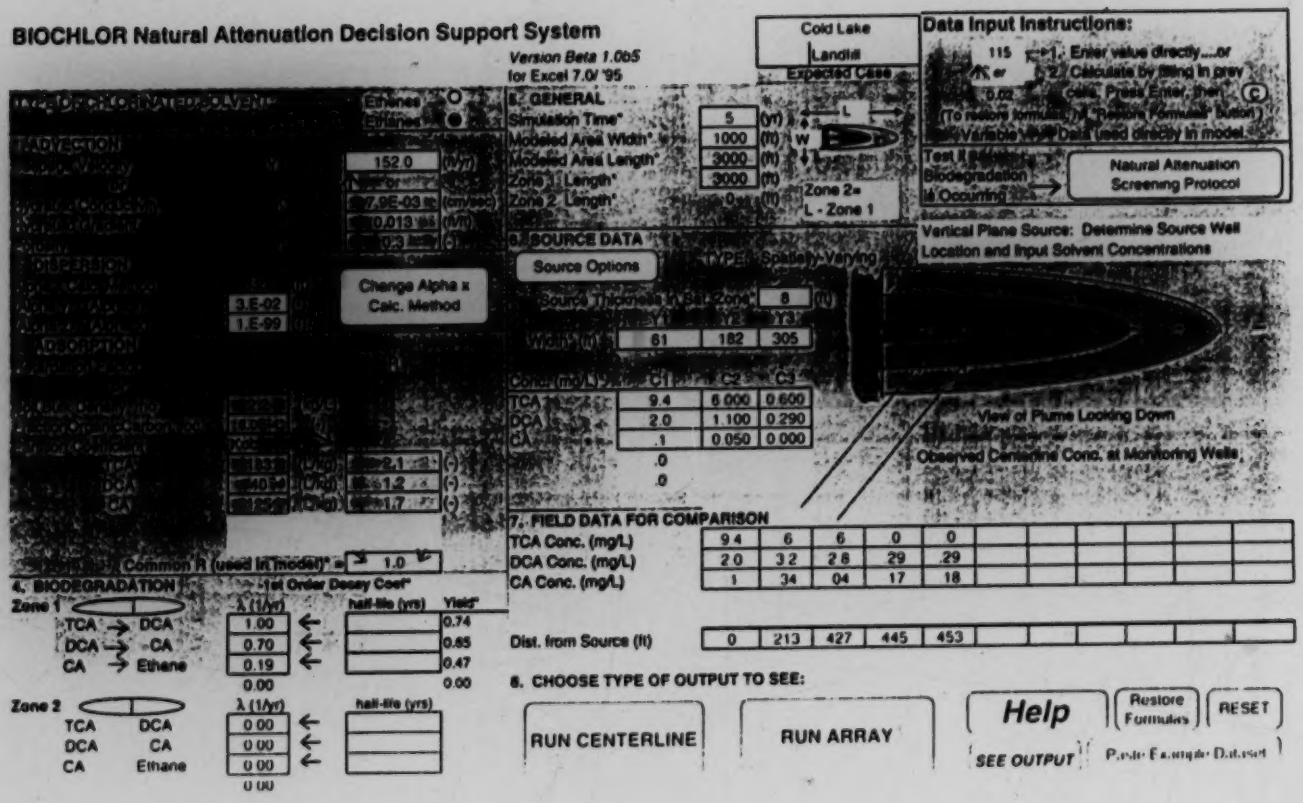
Log ⟺ Linear

Time: 5 Years

Return to Input

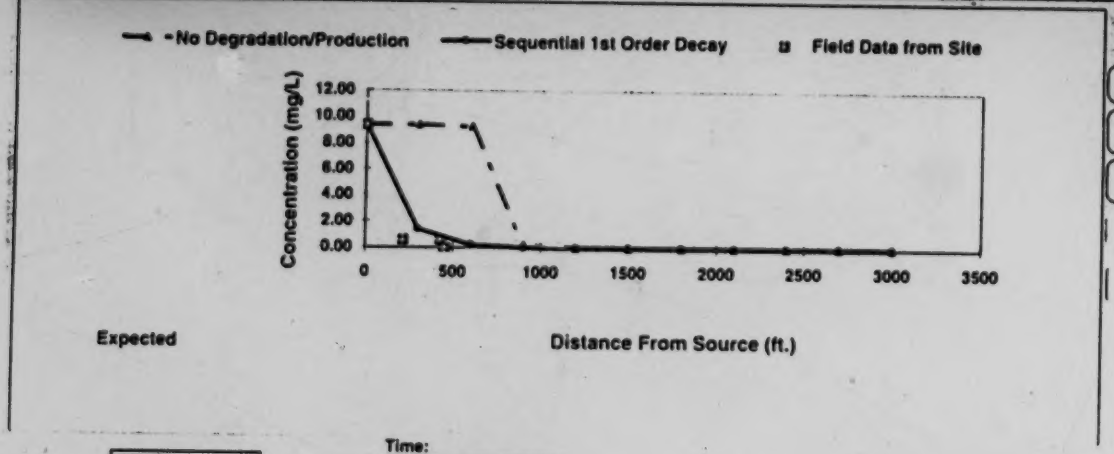
To All

To Array


BIOCHLOR Natural Attenuation Decision Support System
Version Beta 1.0b5
for Excel 7.0/ '95
Cold Lake
Landfill
Expected Case
Data Input Instructions:
1. Enter value directly....or
2. Calculate by filling in grey cells. Press Enter, then
(To restore formulas, hit "Restore Formulas" button)
Variable Name Data (used directly in model
Test if Biodegradation is Occurring
Natural Attenuation Screening Protocol
2. GENERAL
Simulation Time*
Modeled Area Width*
Modeled Area Length*
Zone 1 Length*
Zone 2 Length*
Zone 2= L - Zone 1
3. SOURCE DATA
Source Options
TYPE: Spatially-Varying
Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations
View of Plume Looking Down
Observed Centerline Conc. at Monitoring Wells
Change Alpha x Calc. Method
Common λ (used in model)*
4. BIODEGRADATION
Zone 1
1st Order Decay Coef*
λ (1/yr)
half-life (yrs)
Yield*
TCA → DCA
DCA → CA
CA → Ethane
Zone 2
7. FIELD DATA FOR COMPARISON
TCA Conc. (mg/L)
DCA Conc. (mg/L)
CA Conc. (mg/L)
Dist. from Source (ft)
8. CHOOSE TYPE OF OUTPUT TO SEE:
RUN CENTERLINE
RUN ARRAY
Help
Restore Formulas
RESET
SEE OUTPUT

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

TCA	Distance from Source (ft)										
	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	9.400	9.400	9.273	0.221	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	9.400	1.360	0.196	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Monitoring Well Locations (ft)										
	0	213	427	445	453						
Field Data from Site	9.400	0.600	0.600	0.000	0.000						



See TCA

See DCA

See CA

Log ⟺ Linear

Time:

5 Years

Return to Input

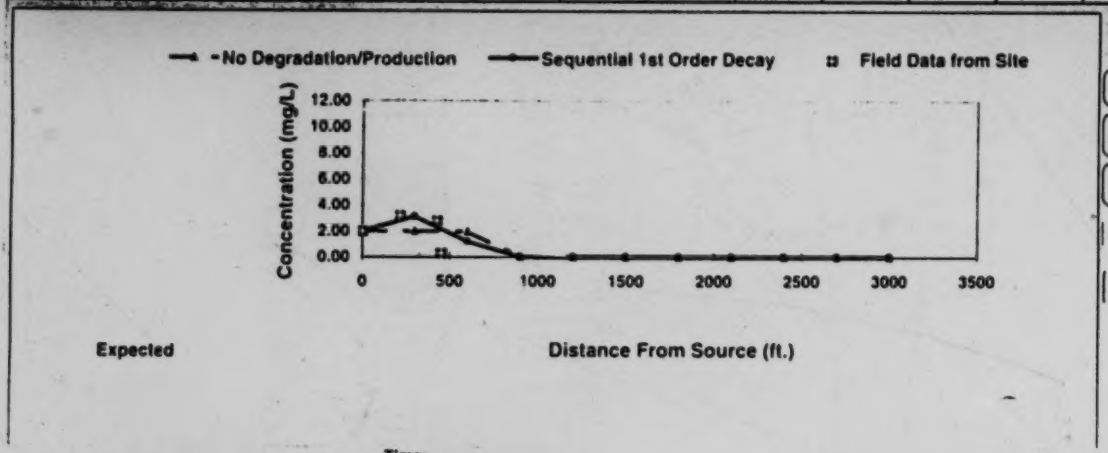
To All

To Array

DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

Distance from Source (ft)

DCA	0	500	1000	1500	1200	1500	1800	2100	2400	2700	3000
No Degradation	2.000	2.000	1.972	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	2.000	3.106	1.163	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000
					Monitoring Well Locations (ft)						
	0	213	427	445	453						
Field Data from Site	2.000	3.200	2.800	0.290	0.290						



See TCA

See DCA

See CA

Log ⟺ Linear

Time:

5 Years

Return to Input

To All

To Array

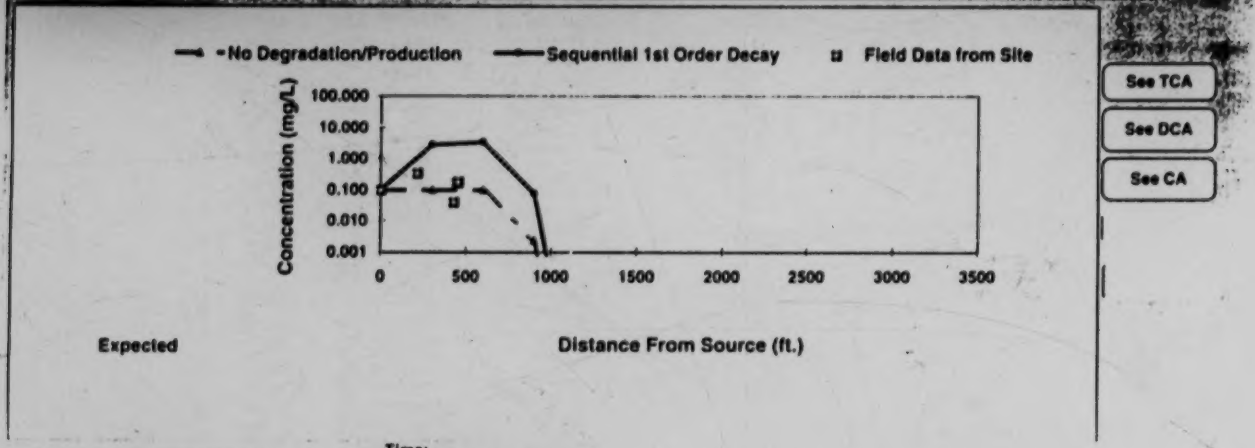
DISSOLVED CHLORINATED SOLVENT CONCENTRATIONS ALONG PLUME CENTERLINE

Distance from Source (ft)

CA	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	0.100	0.100	0.099	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biodegradation	0.100	2.706	3.293	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Monitoring Well Locations (ft)

	0	213	427	446	453						
Field Data from Site	0.100	0.340	0.040	0.170	0.180						



See TCA

See DCA

See CA

Log ⟺ Linear

Time: 5 Years

Return to Input

To All

To Array